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Quota Options for the Red Sea Urchin Fishery in British Columbia for Fishing Season 2000/2001

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ABSTRACT

Annual landings of red sea urchin (*Strongylocentrotus franciscanus*) increased rapidly in the early 1980s for the south coast of British Columbia (B.C.) and in the late 1980s for the north coast, but subsequently were reduced and stabilized by arbitrary quotas. Coastwide landings were 5091 t valued at $ 7.4 M (Cdn.), with 110 licenses issued during the 1998/99 fishing season. Bed areas were obtained by digitizing locations on charts indicated in harvest logbooks. Analyses of recent surveys and review of published survey reports provided estimates of mean density and weights allowing preliminary estimates of red sea urchin biomass in B.C. Based on recent published reports and preliminary estimates in B.C. natural mortality rates of red sea urchins was assumed for fishery management purposes to be between 0.05 and 0.15. Since industry and managers requested an evaluation of the implications of reducing the size limit from present legal size limit (≥ 100 mm test diameter, TD), estimated biomass and quota options were calculated and discussed for a variety of size limits of ≥ 90, ≥ 100, 100-140, 90-120, and 90-130 mm TD for red sea urchins in B.C. Further surveys for red sea urchin density are required, especially in some areas of the south coast of B.C. where surveys are > 10 years old, and in areas in the North Coast that have been heavily fished. Reliable biomass estimates and more accurate estimates of bed areas, natural mortality and recruitment rates for red sea urchins in most areas of B.C. are required to manage this fishery effectively.

RÉSUMÉ

Les débarquements annuels d'oursin rouge (*Strongylocentrotus franciscanus*) en provenance de la côte sud de la Colombie-Britannique (C.-B.) ont augmenté rapidement au début des années 1980 et vers la fin de la décennie pour ceux en provenance de la côte nord. Ils ont ensuite été réduits et stabilisés par l'imposition de quotas. À la grandeur de la côte, les débarquements de la saison de pêche 1998-1999, pour laquelle 110 permis ont été délivrés, ont atteint 5 091 t (valeur de 7,4 M$ can.). La superficie des lits a été obtenue en numérisant sur des cartes les lieux de capture indiqués dans les registres de récolte. L'analyse des relevés récents et l'examen des rapports de relevés publiés ont servi à estimer la densité et le poids moyen et ainsi à obtenir des estimations préliminaires de la biomasse de l'oursin rouge en C.-B. Le taux de mortalité naturelle, aux fins de la gestion de la pêche, a été estimé entre 0,05 et 0,15 à partir des rapports récents publiés et d'estimations provisoires. L'industrie et les gestionnaires ont demandé une évaluation des incidences d'une réduction de la taille limite légale actuelle (≥ 100 mm de diamètre du test, DT) et des options de l'estimation de la biomasse et de quotas ont été calculées et discutées pour une variété des tailles limites de ≥ 90, ≥ 100, 100-140, 90-120 et 90-130 mm de DT, pour l'oursin rouge de la C.-B. Il faudra effectuer d'autres relevés de la densité de l'oursin rouge notamment dans certaines zones de la côte sud de la C.-B. où les relevés datent de plus de dix ans, de même que dans certaines zones de la côte nord où la pêche a été intense. La gestion efficace de l'oursin rouge dans la plupart des zones de la C.-B. exige d'obtenir des estimations fiables de la biomasse et plus exactes de la

superficie des fonds, de la mortalité naturelle et des taux de recrutement de l'oursin rouge dans la plupart des zones de la C.-B.

INTRODUCTION

A commercial dive fishery for the red sea urchin (*Strongylocentrotus franciscanus*) started during the 1970s in British Columbia (B.C.) (Fig. 1, Table 1). Annual landings started to increase rapidly in the early 1980s for the south coast and the late 1980s for the north coast of B.C., but subsequently were reduced and stabilized by arbitrary quotas (Table 1). Coastwide landings were 5091 t valued at $7.4 million (Cdn.) with 110 licenses issued during the 1998/99 fishing season. The history of the management of this fishery is summarized in Campbell and Harbo (1991), Heizer *et al.* (1997), and Rogers and Neifer (1999). A number of papers review various aspects of red sea urchin biology (Bernard and Miller 1973; Mottet 1976; Breen 1980; Sloan *et al.* 1987; Tegner 1989; Campbell and Harbo 1991; Botsford *et al.* 1993, 1994; Lai and Bradbury 1998; Ebert 1998). A few surveys to estimate standing stock of red sea urchins in B.C. during 1976-94 have been published (Breen *et al.* 1976, 1978; Adkins *et al.* 1981; Sloan *et al.* 1987; Jamieson *et al.* 1998a, b, c, d). Based on the results of these surveys Campbell (1998) provided quota estimates for the 1995-96 red sea urchin fishery. Campbell *et al.* (2000) provided quota estimates for the 1998 red sea urchin fishery based on these data and surveys during 1995-97. The results of additional surveys in 1997-99 are summarized in the present paper and Bureau *et al.* (2000a, b, c, d).

The B.C. coast is divided into two main regions, the 'North Coast' and the 'South Coast'. In addition, B.C. is subdivided into Pacific Fishery Management Areas (PFMA) and (PFM) sub-areas for management and economic purposes (detailed charts are not shown in this paper).

Managers have requested additional biomass estimates based on the most recent surveys and that quotas, where possible, be estimated by PFM subarea so they can be applied to the 2000/2001 red sea urchin fishery in B.C. Industry and managers have also requested an evaluation of the present legal size limit ($\geq$ 100 mm test diameter, TD) and implications of reducing the size limit. Industry believe that reductions in the minimum legal size limit would better meet market demands for the best quality gonad (roe) product which is extracted from red sea urchins. Any changes in size limits (including minimum and maximum sizes) would require a precautionary approach to incorporate adaptive management of this valuable resource (Campbell *et al.* 1999).

The purpose of this paper is to (1) summarize catch trends from the sales slips and harvest logbooks, (2) summarize the density surveys conducted to date and estimate biomass of red sea urchins, (3) determine annual quotas based on several size limits options, and (4) discuss the implications of these size limit options on the red sea urchin fishery in B.C.

METHODS

CATCH AND EFFORT

Catch and effort data were summarized from sales slips and from harvest logbooks that fishers completed each day of fishing. Information from sales slips included total weight (pounds) and value (dollars) landed, commercial fishing vessel (CFV) number, date and days fished. Information from the harvest logbooks included location of bed (with diagram), date, landed weight and minutes of diving. The harvest logbooks were not completed by each vessel so the data were used as a sample (CPUE, kilograms per hour) only where both total catch (kg) and effort (minutes) per region were reported per diver for each area per day. Total average annual CPUE were calculated from mean daily vessel CPUE values.

BED AREAS

Commercial bed areas of red sea urchins were indicated on charts or diagrams provided by fishers with their harvest logbooks throughout B.C. during 1982-1996. The detailed bed areas were outlined on hydrographic charts from 1- 9.1m (0-5 fm) below chart datum and were digitized and areas estimated based on sea surface area. The digitized bed areas used in the analyses for this paper are those indicated as harvested during 1982-1996. Estimation of these red urchin bed areas must be treated with caution since the beds were not measured empirically in the field, and the proportion of the suitable substrate types (e.g., boulders or flat bedrock area more suitable than sand or mud) are unknown and may differ from one area to another.

DENSITY AND BIOMASS

Densities of red sea urchins were generally estimated within 1 m^2 quadrats along randomly chosen transects. Details of survey methodology varied between surveys (Breen *et al.* 1976, 1978; Adkins *et al.* 1981; Sloan *et al.* 1987; Jamieson *et al.* 1998a, b, c, d; Bureau *et al.* 2000a, b, c, d). Test diameters (TD, in mm) of urchins were measured on all the surveys except that by Adkins *et al.* (1981). Density estimates from Adkins *et al.* (1981) could be biased since counts were made only at sites where there were more than 1 red sea urchin /m^2. Surveys of sea urchin density were also conducted during 1995 to 1997, using the methodology described by Jamieson and Schwarz (1998). We reanalyzed the data from the 1994-99 surveys using the following methods of estimating mean densities (the 1993 data had a different survey method (Jamieson *et al.* 1998a) so were used unchanged). The present data analysis methods are different compared to those used by Campbell *et al.* (2000) which gave slightly different overall density and biomass estimates. Campbell *et al.* (2000) used overall mean sizes and proportions and applied these to the density estimates for a PFMA or subarea. In contrast, the present analysis methods consider the numbers, sizes, weights and biomass of red sea urchins within each transect length and weighs this according to the total transect lengths sampled

within each PFMA or subarea. N.B. (a) the number of quadrats sampled for urchin density was usually half the potential number of quadrats (i.e. alternate quadrats were sampled) along a transect, and (b) the number of quadrats sampled for urchin sizes could be lower or equal to the quadrats sampled for density along a transect. In some areas high urchin abundance made measuring each urchin logistically unfeasible.

The estimated mean density, $\bar{d}$ (number / m^2) or biomass density (g / m^2), of urchins across a number of transects surveyed in a PFMA or subarea was calculated as

$$\bar{d} = \frac{\sum_t (d_t * L_t)}{\sum_t L_t} \qquad (1)$$

The standard error of the mean density, s_d, was calculated as

$$s_{\bar{d}} = \sqrt{1 - \frac{n}{T}} * \sqrt{\frac{\sum_t (d_t * L_t - \bar{d} * L_t)^2}{n * (n-1) * \bar{L}^2}} \qquad (2)$$

where n is the number of transects, $d_t = N_t / S_t$ is the density at transect t, S_t is the number of quadrats surveyed for density estimates in transect t, N_t is the number of red sea urchins counted for density estimates in transect t, L_t is the length of transect t (or area in square metres since each transect was one metre wide), $\bar{L} = \frac{\sum_t L_t}{n}$ is the mean transect length (or mean area in square metres), and T is the total potential number of transects that could possibly be sampled in the surveyed PFMA or subarea. The expression $\sqrt{(1-n/T)}$ was close to one, because the sample size n was small compared to T.

To estimate the mean densities (number / m^2) or biomass density (g / m^2) for a specific size group (J) the value d_t was substituted with densities ($P_{t,J}$) or biomass ($B_{t,J}$), in equations 1 and 2.

The mean density $P_{t,J}$ (number/ m^2) of red sea urchins of size group J in transect t was calculated as

$$P_{t,J} = \frac{\left(N_t * \frac{\sum_{i \in J} m_{t,i}}{M_t} \right)}{S_t} \qquad (3)$$

The mean biomass density $B_{t,J}$ (g / m^2)of red sea urchins of size group J in transect t was calculated as

$$B_{t,J} = \frac{\left(\frac{N_t}{M_t} * \sum_{i \in J} \left(m_{t,i} * w_i \right) \right)}{S_t} \qquad (4)$$

where J is a subset of possible i values representing a range of test diameters (TD_i) (e.g. $\geq$ 90, $\geq$ 100, 100-140, 90-120, or 90-130 mm TD), $M_t = \sum_i m_{t,i}$ the total number of red sea urchin measured for size in transect t, $m_{t,i}$ is the number of red sea urchins measured in size range i of transect t, and $w_i = 0.0012659 * TD_i^{2.7068}$ is a relationship between mean wet weight (g) and size i (TD in mm) for red sea urchins (Campbell 1998).

Where there were no mean density estimates for a PFM subarea, an overall mean density for all years surveyed within the whole PFMA was used. Where there were no data for a whole PFMA then mean values of data from the nearest or adjacent PFMA were used. The accuracy of these extrapolations is unknown and will require further comparative field surveys.

Standard errors were not directly calculated for densities that included the 1993 survey data since the survey method was different from surveys of later years. However, because an approximate lower 90 % confidence intervals of mean biomass density (L90CIB) was required for each PFM subarea the following method was used. A linear regression, $s_d = b\ \bar{d} / \sqrt{s}$, was used to describe the relation between the standard error (s_d) and the mean biomass density ($\bar{d}$) divided by the square root of the total transect length (s) used for the biomass estimates, with b being a constant estimated using the least squares method. Data analysed from each red sea urchin size limit class group in all PFM subareas and years that were surveyed after 1993 (N=61) resulted in b values of 7.00 (R^2=0.84) for >90 mm TD; 7.14 (R^2=0.85) for >100 mm TD; 7.40 (R^2=0.83) for 100-140 mm TD; 6.91 (R^2=0.74) for 90-120 mm TD; and 6.88 (R^2=0.77) for 90-130 mm TD. The equation $L90CIB = \bar{d}\ (1.0 - 1.64\ b / \sqrt{s})$ was used to calculate the approximate lower 90% confidence interval of the mean biomass density (g/m^2) for each size limit class of red sea urchin and PFM subarea.

Total current biomass of red sea urchins, for each size group, for each PFM subarea was calculated as

$$B_c = A\bar{d} \quad (5)$$

where B_c is the current average biomass (g); A is the commercial urchin bed areas (presented as hectares, but converted to m^2 for biomass calculations) estimated from digitized charts and summed for each PFM subarea; $\bar{d}$ is the estimated mean biomass density (g / m^2) of red sea urchins in a size group (e.g. ≥ 100 mm or 100-140 mm TD). The values for B_c were subsequently converted to tonnes for presentation. Since many of the surveys were conducted >4 years ago and there could be considerable uncertainty in the mean biomass density estimates in some areas we have adopted the Woodby (1992) method by also including the approximate lower 90 % confidence interval (L90CIB) as a reasonable alternative for the $\bar{d}$ values in the B_c calculations.

NATURAL MORTALITY

There are no published estimates of instantaneous natural mortality rate (M) for red sea urchins from northern B.C. Breen (1984) estimated that M ranged from 0.016 to 0.22 for red urchins from 3 sites in southern B.C. and considered a value between 0.1-0.2 to be acceptable. Woodby (1992) estimated M = 0.16 for red sea urchins from the Sitka, Alaska area. Botsford *et al.* (1993) estimated M = 0.14 for a population of red sea urchins in California. Lai and Bradbury (1998) estimated M to be about 0.16 for red sea urchins from Washington. Based on published values Campbell (1998) assumed M to be 0.15 in calculating quotas for the 1995 red sea urchin fishery in B.C. However, all these authors considered growth rates of red sea urchins to be faster (e.g., 4 - 6 years to reach 100 mm TD) than that reported by Ebert (1998) who found tagged sea urchins from Washington and Oregon to take about 10 years to reach 100 mm TD and 50 years to reach 140 mm TD. Ebert (1998) calculated the mean instantaneous total mortality rate (Z $year^{-1}$) of red sea urchins, from a total of twelve samples collected from six locations in Oregon and Washington, to be 0.052 (min. 0.016, max 0.133, lower 95% confidence interval (CI) 0.028, upper CI 0.076); equivalent to a mean annual survival rate of 0.949 (e^{-Z}). The average mortality values reported by Ebert (1998) were generally below those previously reported in the literature. Clearly M will vary between areas and between size classes for red sea urchins in B.C. Although a similar tagging program on red sea urchins in some areas of B.C. has been conducted, further experimental work is required to estimate growth of urchins < 2years (5-30 mm TD). Initial analyses of the growth and mortality data indicated Z (instantaneous natural mortality rate) varied between sites from 0.03 to 0.16 (Campbell *et al.* unpublished data). For the purposes of the present paper, a range of M values from 0.052 to 0.150 (with an approximate mean M of 0.10) was considered for red sea urchins in B.C.

RECRUITMENT

Sloan *et al.* (1987) estimated recruitment to be highly variable between areas and to average about 9.5% of the total number of sea urchins in the size frequencies per area. Little is known about the stock and recruitment relations of red sea urchins in B.C. (Campbell *et al.* 1999).

QUOTA ESTIMATION

A conservative management approach is used to estimate quotas (Q) for the red sea urchin fishery in B.C. A modified surplus production model is used to estimate a maximum sustainable yield (MSY) from a stock that is in the early stages of fishing (Schaefer 1954; Gulland 1971). The model assumes that the MSY occurs when the maximum sustainable fishing mortality is equal to M.

$$Q = X\,M\,B_c \qquad (8)$$

where B_c is the current biomass, M is the instantaneous natural mortality rate and X = a correction factor to insure that a sustainable fishing mortality rate is well below the calculated MSY. We chose the value of $X = 0.20$ in this paper as a reasonably conservative safeguard to account for errors in estimating the lower current biomass values (Caddy 1986; Garcia *et al.* 1989). The correction factor should provide for a conservative harvest per year in a developing fishery where little is known about the productivity of the population. Since equation 8 is derived from a Graham-Schaefer production model, recruitment is assumed to be unaltered by these low fishing levels. Although this approximation was developed for an unexploited virgin stock (B_o) we assumed that $B_c = B_o$.

Caution is required in the interpretation of these calculations for the quota because there are so many assumptions in the parameters used in the oversimplified model. Since many of the surveys were conducted >4 years ago and there could be uncertainty in the mean biomass density estimates in some areas, we have adopted the Woodby (1992) method by also including the approximate lower 90 % confidence intervals as an alternative for the mean B_c calculations.

RESULTS AND DISCUSSION

CATCH AND EFFORT

The number of fishing vessels peaked at 116 in 1990 (Table 1). Coastwide landings peaked in 1992 (Tables 1, 2, 3). Quotas have generally restricted landings in the South Coast since 1985 and in the North Coast since 1993 (Table 1). There was no overall general trend in annual CPUE (kilograms per diver hour) for the red sea urchin fishery in B.C. between 1983-96 (Table 1). The general lack in CPUE trends suggests that either the fishery is at an early stage of development or CPUE data for red sea urchins may not

be used to indicate fishery trends in B.C. Fishermen have increased search time for high quality urchins in response to recent changes in market demands and the implementation of an individual quota scheme. Also, fishermen may be maintaining high CPUE values, through serial depletion, by moving to unexploited sea urchin beds within a PFMA suggesting that CPUE would not decline until most legal-sized sea urchins were removed from most of the areas in the PFMA. There is a need to re-examine the distribution of effort and variability of CPUE data on a smaller spatial scale (*e.g.* by bed) than the PFM subarea level to determine whether CPUE is an appropriate index of red sea urchin abundance. Additional detailed work on updating the data base on bed locations and areas for the fishery during 1997-99 is underway.

Density and Biomass

In general, there was considerable variation in the size structure and densities of local red sea urchin populations. Estimated mean densities (number / m^2) and mean biomass density (g / m^2) by each size group of red sea urchins varied between PFM subareas and years (Tables 4, 5). Generally, density and biomass density were highest for the widest size limit, $\geq$ 90 mm TD, and lowest for the narrowest size limit, 90-120 mm TD, for the size groups examined for each PFM subarea (Fig. 2, Tables 4, 5). Although mean densities for 100-140 mm TD were generally lower than those for $\geq$ 100 mm TD, those for $\geq$ 100 and 90-130 mm TD were similar. In contrast there was a general lowering trend of mean biomass density from $\geq$90, $\geq$100, 100-140, 90-130, to 90-120 mm TD (Fig. 2, Tables 4, 5). An analysis of variance of all log-transformed PFM subarea data indicated significant differences ($p<0.05$): post hoc Tukey pairwise comparisons showed significantly ($p<0.05$) lower mean densities between 90-120 mm TD and $\geq$90 mm TD size limits, and significantly ($p<0.05$) lower mean biomass densities between 90-120 mm TD and two other size groups, $\geq$100 and $\geq$90 mm TD; all other size group comparisons were not significantly different (Tukey pairwise comparisons, $p>0.05$).

The predicted lower 90 % confidence intervals for mean biomass densities for 100-140 mm TD for each PFM subarea were presented in Table 6, as an example, and summarized for the different size groups for each region of B.C. in Table 7.

As the fishery progresses, the average density and biomass of the size group of urchins being exploited may decrease. Fishery-independent surveys of red sea urchin populations in heavily harvested areas should be repeated. Although port sampling is not conducted at present, temporal changes and area differences in size frequency, mean weights, and gonad quality of commercial-sized individuals could be monitored by sampling harvested red sea urchins at ports and or at commercial processing plants.

Bed Areas

The total estimated bed area was 50,205.2 ha for the North Coast and 9,669.2 ha for the South Coast as of 1996 (Table 6a). Estimated bed areas differed for each PFM subarea and increased by an average 26.8 % between 1994 and 1996 (Campbell *et al.* 1999).

Using charts to estimate bed areas is crude, especially as each location may have different substrate surface areas. The harvest logbooks provide an historical cumulative estimate of fishable sea urchin areas but may include a few areas that no longer have viable red sea urchin populations. There may be areas still unexplored, especially in the North Coast, that may contain substantial unfished "virgin" populations that have not been included in the bed area estimates. Bed area estimates probably provide the most uncertainty of all the estimates used to calculate red sea urchin biomass. The most recent bed area estimates for the 1997-99 logbooks have yet to be digitized and calculated.

In some areas there may be large numbers of red sea urchins deeper than 9.1 m (D. Bureau, unpublished data; W. Bradbury, Washington State Fisheries and Wildlife, personal communication). Estimating bed areas in the reasonably shallow depth range (1 – 9.1m) probably provides conservative bed area values to the estimation of red sea urchin biomass. In addition, the present method of multiplying the mean density estimated over the whole PFM subarea by the total bed area is a more conservative method to estimating biomass than multiplying the density by the total coastline area in the PFM subarea.

The records of log book bed area entries should be made on an annual basis rather than a cumulative basis on charts. Clear identification of beds in relation to the amount of red sea urchins removed from each bed needs to be recorded carefully by fishers and on grounds observers to allow detailed stock analyses on a bed by bed and/or PFM subarea basis in both the North and South Coasts. Although there has been an on-ground observer in the North Coast, to date there have not been any on-grounds observers for the South Coast.

BIOMASS AND QUOTA

Red sea urchin biomass (B_c) differed considerably between PFM subareas (Table 6). Total biomass of red sea urchins in the 100-140 mm TD size group was estimated at 242,952 t for the North Coast and 43,864 t for the South Coast; lower 90 % values were 173,847 t and 25,137 t, respectively (Table 6). These biomass and quota estimates must be treated with caution, especially when considering how inaccurate the bed estimates of viable red sea urchin populations may be.

If the size limit of $\geq$100 mm TD is to remain the same, and considering fishermen tend to select sea urchins close to legal size for better gonad quality, the more appropriate quota estimate should be made from B_c calculated from the 100-140 mm TD size group (Tables 6, 7). Choice of a conservative quota probably should be based on M values $\leq$ 0.10 which would suggest that the overall B.C. coastwide 2000/2001 quota should be between 2,982.9 and 5,736.3 t, based on the mean densities, or between 2,069.4 and 3,979.7 t, based on the approximate lower 90 % confidence interval estimates (Tables 6, 7).

If a lower size limit of ≥90 mm TD is considered feasible we recommend that a precautionary approach should include (a) the institution of a maximum size no larger than 130 mm TD, (b) a quota based on a low fishing mortality of ≤ 0.02 (M≤0.10) (Table 7), (c) biomass estimates be based on the lower 90 % confidence limits in areas where red sea urchin abundance estimates are uncertain (e.g., surveys that are > 5 years old), (d) an adaptive management approach be taken by identifying certain PMF subareas to allow testing the feasibility and suitability of lower size limits by fishermen, managers and biologists.

Although we examined two alternative formulations, proposed by Garcia *et al* (1989) (i.e., equations 7a and 8a, based on the Schaefer (1954) and Fox (1970) production models), to estimate Q and MSY by including current yield (Y_c) in an exploited population, both formulae were unstable when attempting to obtain MSY estimates below Y_c. Garcia *et al* (1989) also indicated that these formulae are unstable under other conditions. Die and Caddy (1997) question whether any simple approximation method alone, in obtaining sustainable yield indicators from biomass estimates, can provide a safe yield target. They advocate use of low conservative targets for fishing mortality and several biological reference points (BRPs) as a precautionary approach. Lai and Bradbury (1998), through simulation of red sea urchin populations in Washington, suggested that target harvest rates should be well below biological references points such as F_{max} = 0.48 (fishing mortality at which Y/R is maximized) and $F_{0.1}$ = 0.19 (at which slope of Y/R curve is 10% of the slope at origin) calculated from a yield per recruit model. Campbell and Meynert (Table 3 in appendix B), using a yield per recruit analysis, found a more conservative BRP of $F_{0.35}$ = 0.05 and 0.09 for a size limit of ≥ 100 mm TD and 90-130 mm TD, respectively.

If stock assessment and management is needed on a bed by bed and up to date basis, landings will be required in a timely way (within one year). A 3 (or longer) year periodic rotation of fishing grounds would provide for easier monitoring of the fishing fleet and landings and allow timely analysis of up to date landings data. Three or six year rotation of fishing grounds would also allow recovery of the harvestable stock through recruitment and growth. Botsford *et al.* (1993) and Lai and Bradbury (1998) consider periodic harvest schedules (rotation), although not increasing cumulative yield, are biologically beneficial, reduce variability of yield, risk, and probably management and enforcement costs.

Size Limits

The influence of different size limits and fishing mortality rates on yield and egg per recruit values, where recruitment was constant, were reported by Campbell and Meynert (Appendix B) for a red sea urchin population in B.C. The long-term effects of different harvesting rates and size restrictions on a red sea urchin population, using a stochastic yield model, were examined by Hajas *et al.* (Appendix A). The general results of these analyses are summarized as follows. Minimum size limits of ≥70 and ≥90 mm TD are clearly less precautionary than that of ≥100 mm TD. Adding a lower maximum size to a

minimum size reduces yield but increases the reproductive potential and consequently reduces the potential for collapse of red sea urchin populations. Low fishing mortality rates (e.g., ≤ 0.02) are precautionary and may reduce the influence of size limits. However, having both minimum and maximum size limits and a low fishing mortality provide for a precautionary approach to exploiting red sea urchins populations when determining quotas from uncertain natural mortality and biomass estimations for particular PFM areas.

Although the results of the size limit analyses are robust, they should be treated as preliminary and with some caution since a number of factors (e.g., changes in natural mortality and density effects on growth, mortality and reproductive rates, and roe quality) were not taken into account.

The commercial quality of red sea urchin roe is based on a combination of criteria such as colour, texture, size and taste. Generally, good quality roe from red sea urchins is considered to have a yellow/gold consistent colour, firm texture (growing or premature gonads), sweet taste and of medium size which is mainly found in the approximately 90 – 120 mm TD size range. Poor quality roe is generally considered to have variable yellow/brown colour, soft texture and or oozing gametes (from mature, post spawn or spent gonads). Red sea urchins >130 mm TD generally have large gonads and inconsistent colour quality which are less desirable by the industry than smaller mature individuals. There is a reproductive annual cycle with the timing of the spawning season varying within the period from February to September depending on local environmental conditions such as food availability and temperature (Bernard 1977). Gonads increase in size usually from September to January (Kramer and Nordin 1975). The effect of food quality and availability to support growth and reproduction are important limiting factors on urchin stocks. Although red sea urchins are omnivorous grazers, kelps, such as *Nereocystis leutkeana*, provide optimal growth and gonad quality (Vadas 1977; Bureau *et al.* 1997; Morris and Campbell 1996). In areas of low supply or quality of food, individuals may relocate nutrients causing poor quality gonads thereby reducing reproduction potential of local red sea urchin populations. The influence of adult age, especially in large old red sea urchins, on low egg production, senescence or of poor quality and low survival of larval offspring is unknown.

Breen (1984) argued that a size limit could be used to protect sufficient reproductive potential in an attempt to insure that recruitment did not fall below replacement. A special argument for a maximum size limit can be made for red sea urchins as adult urchins may provide a spine cover for juveniles that is necessary for good survival (Tegner and Dayton 1977). Minimum and maximum size limits would leave enough large adults to protect the settlement of juveniles, such as used in Washington State (Lai and Bradbury 1998). Breen (1984) suggested that using a size limit as the only control mechanism to prevent recruitment overfishing would not be achieved with the ≥ 100 mm TD size limit that is presently used. A larger size limit would be required to prevent recruitment overfishing but would be larger than the industry's upper limit for market quality. Breen (1984) recommended that a better way of preventing recruitment

overfishing was "controlling effort or catch in such a way as to protect local stocks from over harvesting".

The influence of market demand for high quality small sized gonads may cause fishermen to concentrate fishing only on a small size range (e.g., 90 –110 mm TD) of red sea urchins even though the quota may be based on a legal size limit of ≥ 90 mm TD or 90 – 130 mm TD. This would result in a higher fishing mortality on the small size range than was originally intended by the managers. Clearly setting a quota on the appropriate size range that will be harvested in an area will ensure less deviation from the intended fishing mortality on local red sea urchin populations. Monitoring harvested red sea urchins at ports and or at commercial processing plants will provide temporal changes and area differences in size frequency, mean weights, and gonad quality of commercial-sized individuals, and provide a tool to assess the appropriate size range to set quotas.

Lai and Bradbury (1998) conducted simulation models to examine the relative merits of harvest rates, size limits and periodic harvesting on red sea urchin populations in Washington. They found that there was approximately twice the risk of stock collapse without a minimum size limit than with a size limit at different fishing rates. They also found that the probability of sustainability of red sea urchin populations would increase substantially by restricting effort or catch and by increasing the period between harvests (e.g. from 1 to 5 year rotations).

There are a number of complex density dependent compensatory and depensatory mechanisms that red sea urchins may elicit in growth, mortality, increased survival of juveniles due to protection by adult spine canopies, spawning success, roe quality and egg viability. A stock at low density levels may impact on the population negatively, e.g. "the Allee affect" (Allee 1931), reducing the reproductive success of the animals. This is particularly important in organisms that are broadcast spawners. Levitan *et al.* (1992) found that fertilization success was a function of the number of red sea urchins, distance apart, position in the cluster, flow direction and velocity of the current, etc. For animals that show this type of fertilization, this is a factor that should be considered in the management system in providing various forms of harvest refugia (e.g. size restrictions, catch limits through quotas or rotating spatial harvests and spatial closures) (Botsford *et al.* 1993; Quinn *et al.* 1993; Pfister and Bradbury 1996; Levitan and Sewell 1998). Ebert (1998) found potentially little Allee effects on growth of red sea urchins in Oregon and Washington using simulation techniques. He recommended not to automatically assume Allee effects are important in local areas without some evaluation, such as incorporating sensitivity analyses in dynamic modelling methods.

In addition to resource monitoring through fishery independent surveys, additional biological information is clearly required on age estimation and on the variation of growth, mortality and recruitment rates for production modeling of red sea urchin populations in different areas of B.C.

RECOMMENDATIONS

(1) Biomass and quota estimates in this paper should be considered only as a preliminary indication of the status of red sea urchin stocks in B.C.

(2) If a lower size limit of ≥90 mm TD is considered feasible we recommend that a precautionary approach could include:
(a) the institution of a maximum size no larger than 130 mm TD;
(b) a quota based on a low fishing mortality of ≤ 0.02 (M ≤0.10);
(c) biomass estimates be based on the lower 90 % confidence limits in areas where red sea urchin abundance estimates are uncertain (e.g., surveys that are 5 years old);
(d) initially an adaptive management approach be taken by identifying certain PMF subareas to allow testing the feasibility and suitability of lower size limits by fishermen, managers and biologists;
(e) monitoring harvested red sea urchins at ports and or at commercial processing plants will provide temporal changes and area differences in size frequency, mean weights, and gonad quality of commercial-sized individuals, and provide a tool to assess the appropriate size range to set quotas in the future.

(3) Surveys for the abundance estimates of red sea urchins in alternative areas in B.C. should be conducted on an annual basis. Areas with no surveys for over 10 years and for areas that have been heavily fished should be considered a priority.

(4) More accurate estimates of bed areas holding viable populations of red sea urchins are required. Bed areas fished on an annual basis need to be recorded and an update of bed areas fished during 1997-1999 is needed.

(5) Further research is required to understand age, and growth, mortality and recruitment rates of red sea urchins in B.C. to assist with production modeling.

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Table 1. Annual red sea urchin landings (tonnes), value and effort for British Columbia, 1978-96, as reported on sales slips and harvest logs.

Year	Type and Number of Licenses issued	South Coast [1] Quota (t)	North Coast Quota (t)	Number of Vessels with Landings	Total Vessel Fishing Days	Coastwide Landings (t)	Landed Value ($.10^3$)	Whole Landed Value ($/t)	Mean CPUE [2] (t/vessel day)	Mean CPUE [3] (kg/diver hr)
1978	C			4	54	75	16	213	1.4	-
1979	C			29	298	317	76	240	1.1	-
1980	C			18	331	333	84	252	1.0	-
1981	C	136		18	127	116	34	293	0.9	-
1982	C			21	195	160	56	350	0.8	-
1983	Z 64			36	825	986	358	354	1.2	311
1984	Z 85			47	1150	1764	712	403	1.6	281
1985	Z 86	1803		46	1086	1815	764	419	1.7	360
1986	Z 103	1500		67	1534	2067	1011	455	1.4	363
1987	Z 184	1633		97	1807	2118	1148	541	1.2	325
1988	Z 184	1678		84	1249	2116	1241	587	1.7	296
1989	Z 240	1644		109	1542	2658	1631	614	1.7	360
1990	Z 188	1668		116	2651	3158	1953	618	1.2	298
1991	Z 102	1531		89	3862	6831	4187	613	1.8	363
1992	Z 108	1554		110 [4]	6222	12982	8662	616	2.1	388
1993	Z 107	1401	5400	103	3364	6388	5373	841	1.9	340
1994	Z 110	1543	5897	98	3978	5829	8066	1384	1.5	325
1995	Z 108	1386.8	5455	108	4167	6585	11350	1724	1.6	325
1996	Z 109	1264.7	5360	109	3536	5753	11358	1974	1.6	340
1997/98 [5]	Z110	1,702	8150	109	5292	8451	13999	1656	1.6	
1998/99	Z110	968	4635	110	3282	5091	7366	1447	1.6	

[1] South Coast quota includes exploratory areas, North Coast quota was new in 1993.
[2] From sales slip data. [3] CPUE from harvest logbook data.
[4] Larger than the number of licenses issued due to license transfers.
[5] Fishing season changed from calendar year to market driven year (July to June), 1997/98 season January 1, 1997, to June 30, 1998.

Table 2. Red sea urchin annual landings (tonnes) by South Coast Management Area 1971 to June 1999, as reported on fish slips and harvest logs. 1994 to 1999 catch data corrected to use Validation & Harvest logs only.

	SOUTH COAST MANAGEMENT AREAS																		
	East Coast Vancouver Island											West Coast Vancouver Island							Total
Year	11	12	13	14	15	16	17	18	19	28	29	20	21	23	24	25	26	27	Landings
1971 to 1973[1]									110.0						254.0				364.0
1974 to 1977[1]		1.4		*	*	1.4			66.0			*		1.3					70.1
1978			*						46.0			29.0							75.0
1979			*	78.0			57.0	133.0	45.0			1.8	0.9	2.5					318.2
1980				18.0			162.0	54.0	97.0			1.8							332.8
1981			20.0	4.0	*		5.3	47.0	22.0						17.0				115.3
1982		2.5		46.0			0.8	11.0	94.0						5.0				158.5
1983[2]	7.8	99.0	264.0	260.0	*	*	59.0	38.0	112.0			24.0		22.0	38.0		62.0		985.8
1984	0.3	437.0	777.3	172.0			33.0	67.4	76.3		5.7	69.1		17.3	103.0		3.9		1,762.3
1985		354.0	492.0	167.0	106.0	5.9	29.0	48.0	77.0		47.0	30.0		96.0	158.0	145.0	15.0	45.0	1,814.9
1986	27.0	548.0	376.0	178.0	56.0	4.4	57.0	129.0	105.0		2.0	40.0		154.0	285.0		2.5	91.0	2,054.9
1987[3]	6.9	420.0	491.0	193.0	32.4		71.0	71.0	123.0	17.0	7.8	17.0		63.0	199.0	95.0	8.3	12.0	1,827.4
1988	2.6	534.0	480.0	78.0	21.0	2.3	*	22.0	78.0			74.0		13.0	250.0	66.0		58.0	1,678.9
1989		569.0	493.0	122.0	6.7		9.0	64.0	57.0		1.6	15.0			223.0	39.0		86.0	1,685.3
1990	84.8	437.6	428.4	56.6	1.2	0.6	43.0	46.5	58.6	0.3	1.8	7.9		59.7	215.1	56.8		68.1	1,567.0
1991	36.4	358.7	370.7		8.6		26.6	94.8	27.2		14.1	31.2	2.7	58.4	185.1	115.8		121.1	1,451.4
1992	8.0	531.0	320.0				103.0	36.0	86.0		4.0	56.0	9.0	31.0	200.0	10.0		65.0	1,459.0
1993	55.5	329.0	184.0				21.0	104.7	17.3			14.5		40.4	92.0	7.0	2.0	50.0	917.4
1994	17.0	348.0	168.0				4.0	59.0	14.0		1.0	3.0		54.0	111.0	50.0		49.0	878.0
1995	34.0	364.0	175.0				28.0	69.0	15.0		9.0	20.0		57.0	199.0			98.0	1,068.0
1996	38.0	344.0	238.0				25.0	112.0	7.0		10.0	33.0		46.0	122.0			70.0	1,045.0
1997/98	61.0	594.0	426.0		2.3		26.0	67.0	40.0		16.0	32.0		54.0	132.0			85.0	1,535.3
1998/99	49.7	285.2	196.4				26.9	85.3	21.1		2.9	22.5		31.5	107.6			48.2	877.3
1971 to June 1999	429.0	6,556.4	5,899.8	1,372.6	234.2	14.6	785.8	1,358.7	1,394.5	17.3	122.9	521.8	12.6	801.1	2,895.8	584.6	93.7	946.4	24,041.8

* Less than 500 kg.

[1] Data for each year cannot be published separately.

[2] Mandatory log book under Z licence came into effect in 1983.

[3] Sales slips were combined for red and green sea urchins in 1987, were later separated by price criteria, but 320 t remains missing in area table.

Table 3. Red sea urchin annual landings (tonnes) by North Coast Management Area 1984 to June 1999, as reported on fish slips and harvest logs. 1994 to 1999 catch data corrected to use Validation & Harvest logs only.

	NORTH COAST MANAGEMENT AREAS											
Year	1	2E	2W	3	4	5	6	7	8	9	10	Total Landings
1984	2.2											2.2
1986											12.0	12.0
1987					23.0			179.0	91.0			293.0
1988					73.0	11.0	7.3	314.0	32.0			437.3
1989	0.2	223.0		1.6	116.0	1.3	168.0	217.0	65.0		180.0	972.1
1990		26.6	10.7	24.5	156.8	265.3	67.1	1,040.1				1,591.1
1991		333.1	2.7	143.3	1,026.7	2,577.3	77.7	774.7	114.6	24.5	304.9	5,379.5
1992		1,111.0		1.0		3,294.0	4,063.0	2,763.0	140.0	114.0	38.0	11,524.0
1993	97.0	189.0	88.9	127.2	1,008.0	463.0	2,103.0	1,012.0	43.4		215.3	5,346.8
1994	221.0	402.2	167.4	173.0	687.0	1,056.0	1,244.0	861.0	57.0	46.0	164.0	5,078.6
1995[1]	258.0	440.2	256.3	48.0	940.0	1,280.0	1,053.0	1,076.0	111.0	49.0	224.0	5,735.5
1996	259.0	365.0	241.8	66.0	851.0	1,156.0	1,213.0	833.0	122.0	10.0	248.0	5,364.8
1997/98	582.0	718.7	311.1	62.0	1,076.0	1,107.0	2,175.0	870.0	112.0	41.0	152.0	7,206.8
1998/99	276.2	438.1		38.8	595.1	741.8	1,373.6	526.2	87.6	36.8	191.4	4,305.6
1984 to June 1999	1,695.6	4,246.9	1,078.9	685.4	6,552.6	11,952.7	13,544.7	10,466.0	975.6	321.3	1,729.6	53,249.3

[1] Area 106 = 115.3 t

Table 4. Summary of estimated mean density (number/m^2) and mean biomass (g/m^2) of red sea urchins in British Columbia by PMF subarea, obtained from broad-brush surveys during 1993 - 1999. Data include analyses from Jamieson et al. (1998a, b, c, d), Campbell et al. (1998), and present study. NQCI, EQCI and WQCI refer to north, east and west areas of the Queen Charlotte Islands. QCStrait refers to Queen Charlotte Strait. C. Georgia St refers to Central Georgia Strait (Comox and Hornby Is. Areas). SE = standard error. Standard errors were not included for the 1993 surveys or if fewer than 5 transects were surveyed.

PMF			Urchin density for each size group (mm TD)												Mean biomass for each size group (mm TD)											
Subarea	Year	Survey	Total Transect		≥ 100		≥ 90		100-140		90-120		90-130		Total Transect		≥ 100		≥ 90		100-140		90-120		90-130	
			Number	Length (m)	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Number	Length (m)	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
North coast of B.C.																										
1.001	94	NQCI	5	764	1.53	0.33	1.98	0.42	1.52	0.33	1.59	0.36	1.84	0.40	5	764	744.4	155.8	868.6	179.9	729.8	159.1	612.2	136.6	761.2	167.1
1.002	94	NQCI	15	1685	2.89	0.57	3.56	0.70	2.79	0.55	2.50	0.47	3.26	0.67	15	1685	1471.4	297.9	1657.3	334.5	1369.7	276.6	958.0	177.9	1412.5	302.1
1.003	94	NQCI	16	1795	1.26	0.37	1.34	0.39	1.05	0.35	0.49	0.17	0.82	0.27	16	1795	815.3	222.4	836.3	226.4	604.2	204.7	201.4	73.5	401.9	134.0
1.007	94	NQCI	9	2859	0.54	0.20	0.60	0.23	0.47	0.17	0.30	0.13	0.43	0.17	9	2859	323.3	121.3	340.5	128.7	257.6	96.0	118.6	49.8	198.0	78.7
2.003	93	EQCI	5	557	0.42		0.57		0.42		0.39		0.53		5	557	221.3		263.7		221.3		146.3		229.4	
2.007	93	EQCI	6	476	0.95		1.34		0.90		1.00		1.18		6	476	498.3		606.4		447.8		365.7		474.9	
2.008	93	EQCI	7	1070	0.53		0.71		0.51		0.54		0.64		7	1070	273.2		324.5		254.4		205.7		264.9	
2.010	93	EQCI	4	557	0.42		0.44		0.37		0.15		0.25		4	557	262.5		268.2		218.4		62.0		122.9	
2.011	93	EQCI	8	589	0.85		1.10		0.78		0.78		0.93		8	589	463.1		533.7		393.0		292.6		381.5	
2.012	93	EQCI	6	3234	0.07		0.09		0.07		0.07		0.09		6	3234	36.1		41.5		36.1		29.5		36.1	
2.014	93	EQCI	9	1047	0.47		0.69		0.47		0.54		0.61		9	1047	224.3		285.8		224.3		190.0		231.3	
2.015	93	EQCI	6	230	0.31		0.38		0.26		0.21		0.28		6	230	185.3		205.4		142.8		78.8		120.3	
2.017	93	EQCI	11	628	1.13		1.54		1.08		1.11		1.38		11	628	586.6		699.0		532.5		411.0		571.9	
2.018	95	EQCI	11	949	0.77	0.24	1.03	0.33	0.76	0.23	0.82	0.25	0.96	0.30	11	949	367.8	117.3	439.7	141.3	358.1	113.5	305.5	87.4	385.1	117.8
2.019	95	EQCI	5	712	0.80	0.39	1.07	0.51	0.77	0.37	0.81	0.38	0.98	0.47	5	712	391.9	193.1	468.3	224.5	364.6	176.5	297.3	137.9	403.3	192.0
2.031	95	WQCI	5	532	1.50	0.79	1.75	0.82	1.17	0.63	0.69	0.20	0.97	0.30	5	532	1003.6	577.9	1069.1	581.6	690.0	426.3	245.9	66.6	420.2	140.9
2.033	95	WQCI	4	237	0.41		0.69		0.41		0.55		0.65		4	237	184.5		261.5		184.5		178.7		238.5	
2.036	95	WQCI	5	375	1.08	0.42	1.36	0.52	1.03	0.44	0.85	0.45	1.07	0.55	5	375	612.3	212.7	689.1	234.9	558.2	224.3	327.5	176.8	463.4	246.2
2.049	93	WQCI	2	642	0.06		0.09		0.06		0.07		0.09		2	642	29.7		38.2		29.7		25.7		35.9	
2.050	93	WQCI	2	70	1.21		1.67		1.21		1.51		1.67		2	70	532.7		662.0		532.7		565.2		662.0	
2.053	93	WQCI	1	93	1.35		2.42		1.35		2.23		2.39		1	93	568.6		865.9		568.6		752.3		847.2	
2.055	93	WQCI	1	26	0.40		0.59		0.31		0.47		0.49		1	26	224.1		276.8		138.1		167.3		178.7	
2.059	93	WQCI	5	312	0.09		0.15		0.09		0.14		0.15		5	312	38.1		55.7		38.1		51.6		55.7	
2.060	93	WQCI	3	386	0.09		0.13		0.09		0.12		0.12		3	386	36.4		48.8		36.4		41.2		41.2	
2.063	93	WQCI	6	207	1.13		3.11		1.13		3.11		3.11		6	207	421.7		974.1		421.7		974.1		974.1	
2.064	93	WQCI	2	52	0.27		0.53		0.27		0.52		0.53		2	52	110.8		180.4		110.8		175.5		180.4	
2.068	95	WQCI	4	314	0.81		1.57		0.81		1.46		1.57		4	314	344.6		554.1		344.6		489.9		554.1	
2.069	95	WQCI	1	71	0.00		0.00		0.00		0.00		0.00		1	71	0.0		0.0		0.0		0.0		0.0	
2.071	95	WQCI	2	124	1.14		2.24		1.14		2.17		2.24		2	124	466.1		763.9		466.1		726.5		763.9	
2.074	95	WQCI	1	201	1.15		1.81		1.15		1.68		1.81		1	201	463.9		645.1		463.9		566.8		645.1	
2.075	95	WQCI	4	411	1.91		2.43		1.91		2.10		2.33		4	411	853.5		995.8		853.5		780.1		920.1	
2.078	95	WQCI	2	65	0.00		0.00		0.00		0.00		0.00		2	65	0.0		0.0		0.0		0.0		0.0	
2.079	95	WQCI	3	321	0.37		0.59		0.37		0.50		0.58		2	200	282.8		384.8		117.2		287.0		365.3	
2.080	95	WQCI	1	89	0.57		0.86		0.57		0.77		0.86		1	89	232.8		310.7		232.8		255.6		310.7	
3.001	93	Tsimshian	29	1011	0.75		1.00		0.71		0.69		0.85		29	1011	408.1		476.7		363.0		256.3		353.5	
3.002	93	Tsimshian	6	212	0.31		0.37		0.28		0.21		0.28		6	212	178.8		196.6		150.8		81.9		120.8	
4.001	93	Tsimshian	34	1264	0.59		0.71		0.53		0.41		0.56		34	1264	337.5		373.6		280.7		155.3		246.9	
4.002	93	Tsimshian	8	809	0.44		0.56		0.39		0.35		0.45		8	809	253.2		286.6		203.5		130.9		190.4	
4.002	95	Stephensls	34	2045	1.25	0.24	1.75	0.32	1.06	0.19	1.16	0.21	1.41	0.26	33	1926	790.1	163.8	940.7	184.8	574.2	100.2	443.6	78.0	608.2	105.8
4.004	95	Stephensls	3	194	0.00		0.00		0.00		0.00		0.00		3	194	0.0		0.0		0.0		0.0		0.0	
4.009	95	Stephensls	23	3503	0.30	0.10	0.40	0.14	0.29	0.10	0.30	0.10	0.36	0.12	23	3503	152.6	51.5	179.5	60.9	141.3	46.3	113.7	38.7	150.5	51.3
4.013	93	Tsimshian	3	27	1.27		1.59		1.15		1.23		1.27		3	27	683.9		773.6		565.5		476.8		503.4	
5.011	97	Banks Is.	6	910	0.26	0.16	0.33	0.19	0.24	0.15	0.25	0.16	0.28	0.17	6	910	134.6	75.8	151.4	85.0	113.4	66.3	95.9	61.3	110.0	68.1
5.013	97	Banks Is.	3	393	0.34		0.41		0.26		0.21		0.28		3	393	212.0		230.2		134.5		75.8		118.9	
5.020	97	Banks Is.	26	2596	1.55	0.23	2.06	0.33	1.42	0.23	1.49	0.29	1.75	0.32	26	2596	819.8	113.3	963.5	137.7	698.5	105.9	550.9	105.2	706.6	126.1
5.021	97	Banks Is.	22	2429	0.97	0.23	1.15	0.27	0.82	0.21	0.75	0.19	0.92	0.22	22	2429	550.0	129.3	602.8	138.6	411.3	102.2	293.0	75.2	396.9	96.0

PMF Subarea	Year	Survey	Urchin density for each size group (mm TD)												Mean biomass for each size group (mm TD)											
			Total Transect		≥ 100		≥ 90		100-140		90-120		90-130		Total Transect		≥ 100		≥ 90		100-140		90-120		90-130	
			Number	Length (m)	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Number	Length (m)	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
6.010	94	Campania Is.	30	5028	1.51	0.18	1.91	0.28	1.41	0.18	1.33	0.25	1.61	0.25	30	5028	808.4	94.8	921.5	116.5	713.4	85.6	501.1	85.2	672.6	87.9
6.012	94	Campania Is.	7	524	0.52	0.27	0.64	0.36	0.47	0.27	0.39	0.25	0.53	0.32	7	524	287.5	142.8	322.9	168.2	245.1	141.7	145.0	89.6	231.8	136.6
6.013	93	Kitasoo	32	2434	1.21		1.60		1.14		1.23		1.43		32	2434	612.8		722.9		549.0		462.1		584.5	
6.014	93	Kitasoo	11	762	1.14		1.44		1.03		1.01		1.18		11	762	640.1		722.8		518.0		386.9		491.3	
6.015	93	Kitasoo	8	426	0.64		0.91		0.61		0.69		0.82		8	426	327.1		402.8		298.3		252.4		327.8	
6.016	93	Kitasoo	11	881	0.70		1.07		0.69		0.95		1.03		11	881	309.4		412.2		300.0		334.4		383.2	
6.016	95	Price Is.	27	1333	0.81	0.15	1.32	0.24	0.79	0.15	1.11	0.22	1.24	0.24	27	1333	390.8	71.1	534.4	97.2	372.9	67.7	389.4	78.8	469.7	88.5
6.017	93	Kitasoo	9	520	2.94		3.54		2.84		2.84		3.24		9	520	1424.0		1595.7		1328.2		1115.9		1352.9	
6.017	95	Price Is.	9	554	0.78	0.38	1.06	0.48	0.75	0.37	0.72	0.34	0.89	0.40	9	554	419.1	213.9	499.5	240.3	393.9	198.1	268.7	129.5	370.3	169.1
6.018	93	Kitasoo	3	316	0.23		0.29		0.23		0.25		0.29		3	316	102.6		120.4		102.6		95.4		120.4	
6.019	93	Kitasoo	6	566	0.45		0.64		0.45		0.59		0.62		6	566	189.4		241.5		189.4		213.2		227.9	
7.001	97	Goose	15	1241	0.01	0.00	0.02	0.01	0.01	0.00	0.02	0.01	0.02	0.01	15	1241	2.9	1.7	5.8	2.9	2.9	1.7	5.8	2.9	5.8	2.9
7.002	93	Kitasoo	4	268	1.85		2.59		1.78		2.19		2.41		4	268	887.9		1093.7		820.8		827.8		956.7	
7.003	93	Kitasoo	14	2086	1.10		1.46		1.09		1.22		1.40		14	2086	515.4		620.2		504.9		461.3		567.1	
7.004	93	Kitasoo	4	916	0.61		0.78		0.60		0.62		0.74		4	916	295.4		342.7		281.8		238.3		313.5	
7.008	93	Heiltsuk	5	3016	0.11		0.16		0.11		0.15		0.16		5	3016	47.9		64.0		47.9		52.5		64.0	
7.018	93	Heiltsuk	13	1055	0.58		1.03		0.57		0.94		0.99		13	1055	271.5		397.7		253.6		329.5		357.7	
7.018	94	Heiltsuk	26	1458	1.02	0.28	1.69	0.39	1.01	0.28	1.51	0.35	1.65	0.38	26	1458	467.8	130.0	655.6	156.5	452.7	127.9	541.0	128.5	620.6	149.2
7.018	95	Heiltsuk	36	2028	1.03	0.10	1.72	0.17	1.00	0.09	1.55	0.17	1.62	0.17	36	2028	479.3	49.0	671.6	65.0	450.8	43.9	544.7	56.2	599.9	58.6
7.018	96	Heiltsuk	58	5043	0.97	0.14	1.34	0.18	0.95	0.14	1.13	0.16	1.28	0.18	55	4777	475.5	66.2	587.6	77.5	461.2	65.3	442.2	61.7	534.8	70.6
7.018	97	Goose	23	1199	1.13	0.17	1.78	0.25	1.12	0.17	1.60	0.23	1.73	0.25	23	1199	500.8	77.5	685.8	98.6	494.7	76.8	570.1	82.7	645.0	92.9
7.020	93	Heiltsuk	4	471	0.52		1.04		0.52		0.96		1.04		4	471	216.5		359.8		216.5		315.6		359.8	
7.023	94	Heiltsuk	1	36	0.00		0.00		0.00		0.00		0.00		1	36	0.0		0.0		0.0		0.0		0.0	
7.025	94	Heiltsuk	26	1286	1.28	0.25	1.70	0.32	1.26	0.25	1.35	0.27	1.60	0.30	25	1260	636.0	120.4	758.2	139.7	602.2	119.3	511.5	101.4	665.3	123.1
7.025	95	Heiltsuk	28	1882	0.50	0.16	0.75	0.23	0.48	0.15	0.66	0.20	0.72	0.22	28	1882	232.3	72.3	302.4	92.7	213.6	66.4	240.3	74.0	273.5	83.8
7.025	97	Goose	29	2729	0.02	0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.03	29	2729	6.6	6.6	9.5	9.6	6.6	6.6	8.7	8.8	9.5	9.6
7.026	95	Heiltsuk	7	805	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7	805	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7.026	97	Goose	7	441	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6	372	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7.027	93	Heiltsuk	8	838	0.44		0.70		0.43		0.65		0.69		8	838	193.3		266.8		186.1		232.0		259.6	
7.031	93	kitasoo	10	1026	1.32		1.66		1.30		1.35		1.55		10	1026	624.4		723.6		606.7		518.8		640.1	
7.031	95	Pruela	32	1305	1.02	0.27	1.69	0.41	1.02	0.27	1.56	0.38	1.66	0.40	31	1288	442.5	120.0	632.1	157.7	438.6	119.3	551.0	136.5	609.5	154.2
7.032	93	Heiltsuk	4	730	0.58		0.94		0.58		0.89		0.93		4	730	252.5		352.7		252.5		319.0		342.5	
10.001	93	Heiltsuk	5	2984	0.09		0.16		0.09		0.15		0.16		5	2984	38.0		58.9		37.0		52.8		58.0	
106.002	94	Campania Is.	28	2633	1.75	0.26	2.46	0.34	1.72	0.25	2.13	0.30	2.34	0.32	28	2633	821.2	125.1	1020.8	146.5	783.4	116.8	789.3	111.4	914.5	124.0
South Coast of B.C.																										
11.002	96	QCStrait	32	1369	1.10	0.23	1.24	0.26	0.91	0.21	0.42	0.11	0.72	0.17	31	1339	753.5	154.9	795.0	162.4	573.4	136.8	170.1	45.3	355.9	87.4
12.001	99	JohnstoneSt	13	627	0.48	0.19	0.54	0.21	0.44	0.17	0.30	0.13	0.41	0.17	13	627	273.7	102.9	289.3	108.7	232.2	89.7	121.4	53.5	183.6	76.2
12.002	99	JohnstoneSt	16	830	0.34	0.16	0.38	0.18	0.28	0.12	0.20	0.09	0.25	0.11	16	830	209.9	107.8	220.8	111.1	147.4	69.0	77.1	35.2	110.5	50.6
12.003	94	QCStrait	9	309	1.62	0.57	1.72	0.55	1.21	0.40	0.66	0.17	0.84	0.20	9	309	1120.6	429.1	1147.4	424.4	704.1	262.3	273.9	72.9	381.8	101.4
12.004	94	QCStrait	1	25	0.00		0.00		0.00		0.00		0.00		1	25	0.0		0.0		0.0		0.0		0.0	
12.005	94	QCStrait	11	484	1.00	0.24	1.01	0.24	0.64	0.20	0.12	0.05	0.41	0.14	9	381	963.7	130.8	969.6	131.1	522.2	134.4	62.4	26.1	287.5	87.9
12.006	94	QCStrait	16	1356	0.27	0.09	0.31	0.12	0.20	0.08	0.13	0.08	0.19	0.09	14	1292	199.7	66.5	212.6	71.4	124.1	47.1	55.5	32.8	88.7	42.2
12.007	95	QCStrait	6	225	1.54	0.55	1.58	0.57	1.18	0.54	0.31	0.19	0.73	0.32	6	225	1088.1	339.4	1097.9	345.5	742.9	336.6	131.7	78.1	385.5	160.0
12.008	94	QCStrait	4	485	0.09		0.13		0.06		0.07		0.08		3	280	114.1		132.8		57.1		46.0		57.3	
12.011	94	QCStrait	15	713	1.51	0.33	1.83	0.40	1.35	0.30	1.23	0.27	1.50	0.33	15	713	843.0	201.3	935.6	216.7	688.8	161.0	486.4	107.8	652.6	144.2
12.012	94	QCStrait	2	69	1.73		2.08		1.73		1.60		1.87		2	69	849.3		939.6		849.3		624.7		786.3	
12.013	95	QCStrait	21	1344	1.28	0.41	1.39	0.46	0.97	0.33	0.52	0.23	0.76	0.30	21	1344	871.0	281.3	902.4	290.3	575.4	190.0	213.0	95.3	360.9	140.4
12.013	96	QCStrait	11	332	1.25	0.53	1.54	0.53	1.06	0.47	0.87	0.27	1.08	0.38	10	269	944.2	426.3	1045.0	407.6	730.5	343.9	422.8	123.0	578.3	215.7
12.014	96	CapeSutil	8	809	0.85	0.70	1.21	1.03	0.82	0.67	1.03	0.88	1.11	0.94	6	609	530.4	437.1	660.4	555.6	489.0	396.3	493.4	419.8	557.1	462.3
12.015	94	QCStrait	2	57	2.40		3.20		2.40		2.61		3.20		2	57	1051.2		1270.9		1051.2		914.4		1270.9	

PMF Subarea	Year	Survey	Urchin density for each size group (mm TD)												Mean biomass for each size group (mm TD)											
			Total Transect		≥ 100		≥ 90		100-140		90-120		90-130		Total Transect		≥ 100		≥ 90		100-140		90-120		90-130	
			Number	Length (m)	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Number	Length (m)	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
12.016	94	QCStrait	20	1658	0.88	0.30	1.07	0.36	0.73	0.28	0.46	0.19	0.73	0.27	18	1488	654.4	208.3	714.5	226.1	475.5	183.6	186.2	75.4	368.4	136.1
12.017	94	QCStrait	2	443	0.00		0.00		0.00		0.00		0.00		2	443	0.0		0.0		0.0		0.0		0.0	
12.018	94	QCStrait	18	982	0.95	0.23	1.17	0.28	0.89	0.22	0.74	0.21	0.93	0.24	18	982	537.4	128.5	597.5	141.1	477.2	115.8	293.5	81.0	408.9	104.0
12.019	94	QCStrait	3	258	0.22		0.27		0.16		0.12		0.16		3	258	144.8		157.2		88.2		39.2		65.9	
12.020	94	QCStrait	1	59	2.80		2.80		1.77		0.59		0.89		1	59	2021.8		2021.8		1087.4		226.8		423.9	
12.021	94	QCStrait	2	93	1.70		1.83		1.58		0.76		1.25		2	93	1055.3		1095.5		933.9		310.8		621.6	
12.024	99	QCStrait	2	72	0.48		0.51		0.43		0.27		0.40		2	72	288.5		295.1		233.8		117.9		199.4	
12.036	94	QCStrait	1	83	0.00		0.00		0.00		0.00		0.00		1	83	0.0		0.0		0.0		0.0		0.0	
12.039	94	QCStrait	10	576	0.10	0.10	0.10	0.10	0.10	0.10	0.06	0.06	0.08	0.08	9	529	56.4	57.6	56.4	57.6	56.4	57.6	28.5	29.1	41.0	41.9
12.039	95	QCStrait	16	1203	0.07	0.04	0.07	0.04	0.04	0.02	0.01	0.01	0.02	0.01	15	1050	69.0	40.1	69.6	40.5	29.9	18.3	4.2	2.6	9.3	5.7
12.041	95	QCStrait	7	194	1.62	0.89	1.68	0.95	0.67	0.31	0.22	0.13	0.39	0.20	7	194	1383.2	782.5	1402.4	800.7	436.8	204.3	94.3	53.2	195.1	94.1
13.030	99	Johnstone St	4	162	0.30		0.33		0.27		0.24		0.27		4	162	159.5		170.1		139.6		100.1		122.8	
13.031	99	Johnstone St	5	229	1.50	0.41	1.80	0.41	1.46	0.40	1.34	0.31	1.60	0.35	5	229	746.7	215.7	833.4	215.3	715.4	201.5	522.2	136.4	677.0	161.2
13.032	99	Johnstone St	18	868	1.23	0.30	1.42	0.33	1.19	0.28	0.95	0.22	1.24	0.27	18	868	642.1	158.3	697.1	167.2	606.2	146.1	384.9	89.5	555.0	120.7
13.033	99	Johnstone St	7	463	1.48	0.27	1.83	0.34	1.45	0.27	1.37	0.26	1.63	0.30	7	463	748.7	140.8	849.1	158.8	717.0	135.9	535.7	100.2	696.3	126.5
13.035	99	Johnstone St	9	319	0.65	0.30	0.66	0.30	0.43	0.23	0.18	0.09	0.28	0.15	9	319	473.7	213.9	477.1	214.9	260.0	141.8	78.5	37.7	139.0	75.1
14.005	99	C. Georgia S	2	202	0.23		0.40		0.23		0.34		0.39		2	202	112.9		160.5		104.6		122.4		152.2	
14.007	99	C. Georgia S	9	1383	0.27	0.13	0.34	0.15	0.25	0.12	0.22	0.10	0.29	0.14	9	1383	148.5	67.7	168.2	75.4	134.4	64.1	85.9	41.7	127.6	61.9
14.008	99	C. Georgia S	6	812	0.44	0.14	0.52	0.16	0.42	0.13	0.37	0.12	0.44	0.14	6	812	232.1	78.0	256.7	83.0	215.7	70.8	147.1	48.8	191.9	61.8
14.009	99	C. Georgia S	22	3776	0.25	0.06	0.33	0.07	0.24	0.06	0.26	0.06	0.30	0.06	22	3776	120.4	30.0	144.9	32.3	115.4	28.5	99.4	22.1	122.4	26.2
14.011	99	C. Georgia S	17	1715	0.08	0.06	0.09	0.06	0.07	0.05	0.03	0.02	0.06	0.04	17	1715	52.3	35.9	54.6	37.5	40.9	29.2	11.5	8.2	29.5	21.2
14.012	99	C. Georgia S	5	503	0.17	0.11	0.19	0.14	0.14	0.11	0.12	0.12	0.13	0.13	5	503	101.4	62.5	108.1	67.2	70.4	52.2	49.0	47.1	56.3	54.3
17.001	98	S. Gulf Is.	4	232	0.06		0.06		0.05		0.00		0.03		4	232	39.8		39.8		32.8		0.0		14.9	
17.002	98	S. Gulf Is.	3	231	0.02		0.02		0.01		0.00		0.00		3	231	15.0		15.0		6.4		0.0		0.0	
18.001	98	S. Gulf Is.	6	366	0.14	0.08	0.16	0.10	0.12	0.06	0.07	0.05	0.08	0.06	6	366	91.7	49.9	99.4	55.8	73.4	36.7	27.8	21.7	36.9	29.1
18.002	98	S. Gulf Is.	8	356	0.20	0.10	0.23	0.10	0.14	0.08	0.08	0.06	0.11	0.07	8	356	138.1	62.3	139.8	63.9	80.7	40.4	34.9	25.4	58.1	31.8
18.003	98	S. Gulf Is.	11	677	0.06	0.03	0.06	0.03	0.02	0.01	0.01	0.00	0.01	0.00	11	677	54.8	30.5	54.8	30.5	11.4	7.2	4.5	2.4	4.5	2.4
18.004	99	S. Gulf Is.	8	576	0.24	0.13	0.25	0.13	0.09	0.05	0.02	0.02	0.03	0.02	8	576	209.3	108.7	210.1	109.5	60.7	31.0	9.2	9.5	17.7	11.8
18.005	99	S. Gulf Is.	6	460	0.16	0.09	0.18	0.10	0.15	0.09	0.08	0.05	0.13	0.08	6	460	102.8	52.9	108.0	55.7	86.5	52.8	33.4	20.8	62.8	38.9
18.006	99	S. Gulf Is.	22	2706	0.37	0.13	0.39	0.14	0.24	0.11	0.09	0.04	0.17	0.08	22	2706	273.6	88.8	278.7	90.1	150.3	67.7	38.5	17.8	86.3	42.9
18.009	98	S. Gulf Is.	1	45	0.00		0.00		0.00		0.00		0.00		1	45	0.0		0.0		0.0		0.0		0.0	
18.011	98	S. Gulf Is.	4	176	0.64		0.72		0.49		0.18		0.40		4	176	444.5		467.1		309.8		67.0		207.2	
111.000	96	Cox Is.	6	598	1.99	0.28	2.56	0.30	1.96	0.27	2.25	0.32	2.47	0.29	6	598	897.1	122.5	1055.6	126.0	869.2	112.4	847.7	122.5	982.0	108.9

Table 5. Summary of estimated mean density (number/m^2) and mean biomass (g/m^2) of red sea urchins in British Columbia by PMF subarea, all years combined, obtained from broad-brush surveys during 1993 - 1999. Data include analyses from Jamieson et al. (1998a, b, c, d), Campbell et al. (1998) and present study. 2E and 2W refer to east and west areas of PMF area 2 in the Queen Charlotte Islands.

[a] = PFM subarea 12.014 not included.

PMF		Urchin density for each size group (mm TD)							Mean biomass for each size group (mm TD)						
Subarea	Year	Total Transect		≥ 100	≥ 90	100-140	90-120	90-130	Total Transect		≥ 100	≥ 90	100-140	90-120	90-130
		Number	Length (m)						Number	Length (m)					
North coast of B.C.															
1	94	45	7103	1.39	1.64	1.28	1.01	1.35	45	7103	765.3	835.0	659.8	391.8	598.2
2E	93-95	78	10049	0.48	0.63	0.45	0.44	0.54	78	10049	245.0	290.3	226.9	174.6	231.8
2W	93-95	62	45208	0.65	1.02	0.61	0.84	0.93	61	4407	392.3	500.9	341.8	324.0	392.2
2	93-95	140	14557	0.55	0.77	0.52	0.58	0.67	139	14456	289.9	354.5	261.9	220.2	280.7
3	93	35	1223	0.68	0.89	0.63	0.61	0.75	35	1223	368.4	428.2	326.3	226.1	313.2
4	93-95	105	8343	0.59	0.77	0.53	0.50	0.63	104	7723	350.4	409.8	276.5	203.0	282.0
5	97	57	6328	1.06	1.36	0.95	0.95	1.13	57	6328	579.9	662.7	469.1	357.0	465.5
6	93-95	153	13344	0.94	1.27	0.89	0.98	1.13	153	13344	617.5	722.5	553.4	435.9	560.5
7	93-97	354	29859	0.69	1.01	0.67	0.88	0.97	348	29481	320.9	414.7	309.6	323.7	379.6
10	93	5	2984	0.087	0.163	0.086	0.153	0.162	5	2984	38.0	58.9	37.0	52.8	58.0
106	94	28	2633	1.75	2.46	1.72	2.13	2.34	28	2633	821.2	1020.8	783.4	789.3	914.5
South Coast of B.C.															
11	96	32	1360	1.10	1.24	0.91	0.42	0.72	31	1339	753.5	795.0	573.4	170.1	355.9
12.014	96	8	809	0.85	1.21	0.82	1.03	1.11	6	609	530.4	660.4	489.0	493.4	557.1
111	96	6	598	1.99	2.56	1.96	2.25	2.47	6	598	897.1	1055.6	869.2	847.7	982.0
12 a	94-96	180	11020	0.77	0.88	0.61	0.40	0.56	170	10215	544.1	578.5	378.1	169.6	275.7
12	99	31	1529	0.41	0.45	0.35	0.24	0.32	31	1529	239.76	252.36	186.26	97.19	144.67
13	99	43	2041	1.15	1.35	1.09	0.91	1.14	43	2041	613.40	670.69	552.47	364.04	501.40
14	99	61	8391	0.23	0.29	0.22	0.21	0.26	61	8391	120.60	139.29	110.04	81.35	107.76
17	98	7	463	0.04	0.04	0.03	0.00	0.01	7	463	27.43	27.43	19.63	0.00	7.47
18	98-99	74	3570	0.28	0.29	0.18	0.07	0.13	74	3570	206.32	210.83	111.75	30.24	64.59

Table 6. Quota (tonnes) options for the red sea urchin fishery by PMF subarea, estimated from various natural mortality values applied to current biomass (Bc) calculated from mean and approximate 90% lower confidence interval (CI) biomass values (g/m^2) for commercial red sea urchin sizes 100-140 mm TD, and bed areas fished up to 1996. NB : blank = average values directly from survey data within subarea; a = average values combined for all years surveyed within subarea; b = average values from all surveys in PMF area (may include several subareas and years); c = average values of surveys in PMF area 7 used for subareas of PMF areas 8, 9, 10; d = data from 11.002 copied to 11.001; e = average values of surveys in PMF area 14 used in PMF area 15; f = average values of PMF area 18 used in subareas of PMF areas 17, 19; g = average values of old surveys (1974-85) extrapolated for PMF areas 19, 20, 23, 24, 25, 26, 27, 29, 124, 125, after Campbell et al. (1998), assumed transect length was 1000 m to calculate lower 90% CI of biomass density.

PMF										Quota 0.2 M Bc (of urchins 100-140 mm TD)							
Subarea	Year	NB	Transect		Biomass (g/m^2)		Bed	Bc Biomass (t)		M = 0.052		M = 0.075		M = 0.10		M = 0.15	
			No	Length (m)	Mean	Lower 90 % CI	area (ha) 1996	Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI
North Coast B.C.																	
1.001	94		5	764	729.8	409.2	4837.6	35304.8	19795.3	367.2	205.9	529.6	296.9	706.1	395.9	1059.1	593.9
1.002	94		15	1685	1369.7	964.5	405.0	5547.1	3906.2	57.7	40.6	83.2	58.6	110.9	78.1	166.4	117.2
1.003	94		16	1795	604.2	431.0	2024.2	12229.5	8724.5	127.2	90.7	183.4	130.9	244.6	174.5	366.9	261.7
1.005	94	b	45	7103	659.8	564.7	454.7	2999.8	2567.6	31.2	26.7	45.0	38.5	60.0	51.4	90.0	77.0
1.007	94		9	2859	257.6	199.1	1360.4	3504.1	2708.3	36.4	28.2	52.6	40.6	70.1	54.2	105.1	81.2
2.003	93		5	557	221.3	107.4	339.3	750.9	364.5	7.8	3.8	11.3	5.5	15.0	7.3	22.5	10.9
2.006	93-95	b	78	10049	226.9	199.4	298.0	676.1	594.2	7.0	6.2	10.1	8.9	13.5	11.9	20.3	17.8
2.007	93		6	476	447.8	198.6	469.4	2101.7	932.0	21.9	9.7	31.5	14.0	42.0	18.6	63.1	28.0
2.008	93		7	1070	254.4	160.0	331.9	844.3	531.0	8.8	5.5	12.7	8.0	16.9	10.6	25.3	15.9
2.010	93		4	557	218.4	106.1	2.2	4.9	2.4	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.1
2.011	93		8	589	393.0	196.4	973.4	3825.8	1911.7	39.8	19.9	57.4	28.7	76.5	38.2	114.8	57.4
2.012	93		6	3234	36.1	28.4	212.8	76.8	60.4	0.8	0.6	1.2	0.9	1.5	1.2	2.3	1.8
2.013	93-95	b	78	10049	226.9	199.4	26.2	59.5	52.3	0.6	0.5	0.9	0.8	1.2	1.0	1.8	1.6
2.014	93		9	1047	224.3	140.1	284.5	638.0	398.6	6.6	4.1	9.6	6.0	12.8	8.0	19.1	12.0
2.015	93		6	230	142.8	28.4	128.7	183.8	36.5	1.9	0.4	2.8	0.5	3.7	0.7	5.5	1.1
2.017	93		11	628	532.5	274.6	341.8	1819.9	938.4	18.9	9.8	27.3	14.1	36.4	18.8	54.6	28.2
2.018	95		11	949	358.1	216.9	291.1	1042.5	631.6	10.8	6.6	15.6	9.5	20.8	12.6	31.3	18.9
2.019	95		5	712	364.6	198.7	34.4	125.3	68.3	1.3	0.7	1.9	1.0	2.5	1.4	3.8	2.0
2.031	95		5	532	690.0	326.8	419.6	2895.4	1371.1	30.1	14.3	43.4	20.6	57.9	27.4	86.9	41.1
2.033	95		4	237	184.5	39.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.036	95		5	375	558.2	208.2	95.2	531.2	198.1	5.5	2.1	8.0	3.0	10.6	4.0	15.9	5.9
2.037	93-95	b	61	4407	341.8	279.3	29.0	99.0	80.9	1.0	0.8	1.5	1.2	2.0	1.6	3.0	2.4
2.049	93		2	642	29.7	15.4	193.4	57.3	29.9	0.6	0.3	0.9	0.4	1.1	0.6	1.7	0.9
2.050	93		2	70	532.7	0.0	146.2	779.1	0.0	8.1	0.0	11.7	0.0	15.6	0.0	23.4	0.0
2.051	93-95	b	61	4407	341.8	279.3	27.2	93.0	76.0	1.0	0.8	1.4	1.1	1.9	1.5	2.8	2.3
2.053	93		1	93	568.6	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

PMF Subarea	Year	NB	Transect No	Transect Length (m)	Biomass (g/m^2) Mean	Biomass (g/m^2) Lower 90 % CI	Bed area (ha) 1996	Bc Biomass (t) Mean	Bc Biomass (t) Lower 90 % CI	Quota 0.2 M Bc (of urchins 100-140 mm TD) M = 0.052 Mean	M = 0.052 Lower 90 % CI	M = 0.075 Mean	M = 0.075 Lower 90 % CI	M = 0.10 Mean	M = 0.10 Lower 90 % CI	M = 0.15 Mean	M = 0.15 Lower 90 % CI
2.055	93		1	26	138.1	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.059	93		5	312	38.1	11.9		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.060	93		3	386	36.4	13.9		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.063	93		6	207	421.7	66.1		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.064	93		2	52	110.8	0.0	29.4	32.5	0.0	0.3	0.0	0.5	0.0	0.7	0.0	1.0	0.0
2.065	93-95	b	61	4407	341.8	279.3	27.0	92.4	75.5	1.0	0.8	1.4	1.1	1.8	1.5	2.8	2.3
2.066	93-95	b	61	4407	341.8	279.3	5.8	19.8	16.2	0.2	0.2	0.3	0.2	0.4	0.3	0.6	0.5
2.067	93-95	b	61	4407	341.8	279.3	61.8	211.4	172.7	2.2	1.8	3.2	2.6	4.2	3.5	6.3	5.2
2.068	95		4	314	344.6	108.5	561.9	1936.3	609.5	20.1	6.3	29.0	9.1	38.7	12.2	58.1	18.3
2.069	95		1	71	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.071	95		2	124	466.1	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.074	95		1	201	463.9	66.6		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.075	95		4	411	853.5	342.3		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.078	95		2	65	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.079	95		2	200	117.2	16.6		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.080	95		1	89	232.8	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.087	93-95	b	61	4407	341.8	279.3	32.6	111.4	91.0	1.2	0.9	1.7	1.4	2.2	1.8	3.3	2.7
2.088	93-95	b	61	4407	341.8	279.3	61.9	211.5	172.8	2.2	1.8	3.2	2.6	4.2	3.5	6.3	5.2
2.094	93-95	b	61	4407	341.8	279.3	47.6	162.7	132.9	1.7	1.4	2.4	2.0	3.3	2.7	4.9	4.0
2.095	93-95	b	61	4407	341.8	279.3	68.8	235.3	192.3	2.4	2.0	3.5	2.9	4.7	3.8	7.1	5.8
2.096	93-95	b	61	4407	341.8	279.3	96.6	330.0	269.7	3.4	2.8	5.0	4.0	6.6	5.4	9.9	8.1
2.098	93-95	b	61	4407	341.8	279.3	98.8	337.8	276.0	3.5	2.9	5.1	4.1	6.8	5.5	10.1	8.3
2.100	93-95	b	61	4407	341.8	279.3	11.8	40.2	32.8	0.4	0.3	0.6	0.5	0.8	0.7	1.2	1.0
3.001	93		29	1011	363.0	224.4	724.2	2628.9	1625.1	27.3	16.9	39.4	24.4	52.6	32.5	78.9	48.8
3.002	93		6	212	150.8	25.0	33.0	49.8	8.2	0.5	0.1	0.7	0.1	1.0	0.2	1.5	0.2
3.003	93	b	35	1223	326.3	213.0	73.7	240.4	156.9	2.5	1.6	3.6	2.4	4.8	3.1	7.2	4.7
3.004	93	b	35	1223	326.3	213.0	24.4	79.5	51.9	0.8	0.5	1.2	0.8	1.6	1.0	2.4	1.6
4.001	93		34	1264	280.7	184.8	1074.0	3014.5	1985.1	31.4	20.6	45.2	29.8	60.3	39.7	90.4	59.6
4.002	93-95	a	41	2735	464.6	356.7	848.8	3943.3	3027.7	41.0	31.5	59.1	45.4	78.9	60.6	118.3	90.8
4.003	93-95	b	104	7723	276.5	238.3	875.2	2419.7	2085.4	25.2	21.7	36.3	31.3	48.4	41.7	72.6	62.6
4.004	93-95	b	104	7723	276.5	238.3	55.0	152.2	131.2	1.6	1.4	2.3	2.0	3.0	2.6	4.6	3.9
4.005	93-95	b	104	7723	276.5	238.3	85.5	236.3	203.7	2.5	2.1	3.5	3.1	4.7	4.1	7.1	6.1
4.009	95		23	3503	141.3	112.3	659.4	931.5	740.4	9.7	7.7	14.0	11.1	18.6	14.8	27.9	22.2
4.013	93		3	27	565.5	0.0	738.2	4174.5	0.0	43.4	0.0	62.6	0.0	83.5	0.0	125.2	0.0

PMF Subarea	Year	NB	Transect		Biomass (g/m^2)		Bed area (ha)	Bc Biomass (t)		Quota 0.2 M Bc (of urchins 100-140 mm TD)							
										M = 0.052		M = 0.075		M = 0.10		M = 0.15	
			No	Length (m)	Mean	Lower 90 % CI	1996	Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI
5.009	97	b	57	6328	469.1	397.5	342.5	1606.6	1361.3	16.7	14.2	24.1	20.4	32.1	27.2	48.2	40.8
5.010	97	b	57	6328	469.1	397.5	1506.4	7066.3	5987.7	73.5	62.3	106.0	89.8	141.3	119.8	212.0	179.6
5.011	97		6	910	113.4	67.8	557.0	631.6	377.4	6.6	3.9	9.5	5.7	12.6	7.5	18.9	11.3
5.012	97	b	57	6328	469.1	397.5	395.3	1854.4	1571.4	19.3	16.3	27.8	23.6	37.1	31.4	55.6	47.1
5.013	97		3	393	134.5	52.1	835.6	1124.1	435.6	11.7	4.5	16.9	6.5	22.5	8.7	33.7	13.1
5.014	97	b	57	6328	469.1	397.5	114.6	537.4	455.4	5.6	4.7	8.1	6.8	10.7	9.1	16.1	13.7
5.016	97	b	57	6328	469.1	397.5	525.8	2466.7	2090.2	25.7	21.7	37.0	31.4	49.3	41.8	74.0	62.7
5.017	97	b	57	6328	469.1	397.5	996.2	4673.0	3959.7	48.6	41.2	70.1	59.4	93.5	79.2	140.2	118.8
5.019	97	b	57	6328	469.1	397.5	3.7	17.5	14.8	0.2	0.2	0.3	0.2	0.3	0.3	0.5	0.4
5.020	97		26	2596	698.5	532.0	2174.2	15186.1	11567.0	157.9	120.3	227.8	173.5	303.7	231.3	455.6	347.0
5.021	97		22	2429	411.3	310.0	667.1	2743.9	2067.9	28.5	21.5	41.2	31.0	54.9	41.4	82.3	62.0
5.022	97	b	57	6328	469.1	397.5	2169.9	10178.9	8625.2	105.9	89.7	152.7	129.4	203.6	172.5	305.4	258.8
6.005	93-95	b	153	13344	553.4	495.2	65.7	363.7	325.4	3.8	3.4	5.5	4.9	7.3	6.5	10.9	9.8
6.009	93-95	b	153	13344	553.4	495.2	3230.7	17877.4	15998.2	185.9	166.4	268.2	240.0	357.5	320.0	536.3	479.9
6.010	94		30	5028	713.4	591.3	1671.7	11926.6	9884.2	124.0	102.8	178.9	148.3	238.5	197.7	357.8	296.5
6.011	93-95	b	153	13344	553.4	495.2	99.7	551.6	493.6	5.7	5.1	8.3	7.4	11.0	9.9	16.5	14.8
6.012	94		7	524	245.1	115.1	203.5	498.7	234.2	5.2	2.4	7.5	3.5	10.0	4.7	15.0	7.0
6.013	93		32	2434	549.0	413.9	2545.4	13973.8	10534.7	145.3	109.6	209.6	158.0	279.5	210.7	419.2	316.0
6.014	93		11	762	518.0	290.1	299.9	1553.2	869.8	16.2	9.0	23.3	13.0	31.1	17.4	46.6	26.1
6.015	93		8	426	298.3	122.7	520.1	1551.6	638.3	16.1	6.6	23.3	9.6	31.0	12.8	46.5	19.1
6.016	93-95	a	38	2214	343.9	255.2	903.8	3108.1	2306.1	32.3	24.0	46.6	34.6	62.2	46.1	93.2	69.2
6.017	93-95	a	18	1074	846.8	533.1	510.3	4321.3	2720.5	44.9	28.3	64.8	40.8	86.4	54.4	129.6	81.6
6.018	93		3	316	102.6	32.5	115.4	118.4	37.5	1.2	0.4	1.8	0.6	2.4	0.8	3.6	1.1
6.019	93		6	566	189.4	92.8	109.3	207.1	101.4	2.2	1.1	3.1	1.5	4.1	2.0	6.2	3.0
6.020	93-95	b	153	13344	553.4	495.2	29.8	164.9	147.6	1.7	1.5	2.5	2.2	3.3	3.0	4.9	4.4
6.025	93-95	b	153	13344	553.4	495.2	28.8	159.4	142.6	1.7	1.5	2.4	2.1	3.2	2.9	4.8	4.3
7.001	97		15	1241	2.9	1.9	55.2	1.6	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7.002	93		4	268	820.8	211.9		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7.003	93		14	2086	504.9	370.7	439.2	2217.7	1628.1	23.1	16.9	33.3	24.4	44.4	32.6	66.5	48.8
7.004	93		4	916	281.8	168.8	208.7	588.2	352.2	6.1	3.7	8.8	5.3	11.8	7.0	17.6	10.6
7.005	93-97	b	348	29481	309.6	287.7	56.5	175.0	162.6	1.8	1.7	2.6	2.4	3.5	3.3	5.2	4.9
7.006	93-97	b	348	29481	309.6	287.7	142.4	440.8	409.6	4.6	4.3	6.6	6.1	8.8	8.2	13.2	12.3
7.008	93		5	3016	47.9	37.3		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7.009	93-97	b	348	29481	309.6	287.7	713.1	2207.5	2051.4	23.0	21.3	33.1	30.8	44.2	41.0	66.2	61.5

PMF Subarea	Year	NB	Transect No	Transect Length (m)	Biomass (g/m^2) Mean	Biomass (g/m^2) Lower 90 % CI	Bed area (ha) 1996	Bc Biomass (t) Mean	Bc Biomass (t) Lower 90 % CI	Quota 0.2 M Bc (of urchins 100-140 mm TD) M = 0.052 Mean	M = 0.052 Lower 90 % CI	M = 0.075 Mean	M = 0.075 Lower 90 % CI	M = 0.10 Mean	M = 0.10 Lower 90 % CI	M = 0.15 Mean	M = 0.15 Lower 90 % CI
7.012	93-97	b	348	29481	309.6	287.7	148.8	460.7	428.2	4.8	4.5	6.9	6.4	9.2	8.6	13.8	12.8
7.017	93-97	b	348	29481	309.6	287.7	3.5	10.8	10.0	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3
7.018	93-97	a	153	10517	441.0	388.8	1294.3	5708.3	5032.4	59.4	52.3	85.6	75.5	114.2	100.6	171.2	151.0
7.019	93-97	b	348	29481	309.6	287.7	94.6	292.8	272.1	3.0	2.8	4.4	4.1	5.9	5.4	8.8	8.2
7.020	93		4	471	216.5	95.4	51.8	112.1	49.4	1.2	0.5	1.7	0.7	2.2	1.0	3.4	1.5
7.021	93-97	b	348	29481	309.6	287.7	40.1	124.1	115.3	1.3	1.2	1.9	1.7	2.5	2.3	3.7	3.5
7.023	93-97	b	348	29481	309.6	287.7	51.6	159.6	148.3	1.7	1.5	2.4	2.2	3.2	3.0	4.8	4.4
7.024	93-97	b	348	29481	309.6	287.7	2.6	8.2	7.6	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
7.025	94-97	a	82	5871	200.8	168.9	796.0	1598.1	1344.8	16.6	14.0	24.0	20.2	32.0	26.9	47.9	40.3
7.026	95-97	a	13	1177	0.0	0.0	52.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7.027	93		8	838	186.1	108.1	204.1	379.9	220.6	4.0	2.3	5.7	3.3	7.6	4.4	11.4	6.6
7.028	93-97	b	348	29481	309.6	287.7	19.4	60.2	55.9	0.6	0.6	0.9	0.8	1.2	1.1	1.8	1.7
7.031	93-95	a	41	2314	513.1	383.5	1107.1	5680.1	4246.3	59.1	44.2	85.2	63.7	113.6	84.9	170.4	127.4
7.032	93		4	730	252.5	139.0	308.2	778.3	428.4	8.1	4.5	11.7	6.4	15.6	8.6	23.3	12.9
8.001	93-97	c	348	29481	309.6	287.7	27.1	83.8	77.9	0.9	0.8	1.3	1.2	1.7	1.6	2.5	2.3
8.002	93-97	c	348	29481	309.6	287.7	87.5	270.8	251.7	2.8	2.6	4.1	3.8	5.4	5.0	8.1	7.5
8.003	93-97	c	348	29481	309.6	287.7	5.5	17.0	15.8	0.2	0.2	0.3	0.2	0.3	0.3	0.5	0.5
8.004	93-97	c	348	29481	309.6	287.7	156.2	483.5	449.3	5.0	4.7	7.3	6.7	9.7	9.0	14.5	13.5
8.016	93-97	c	348	29481	309.6	287.7	64.6	200.1	185.9	2.1	1.9	3.0	2.8	4.0	3.7	6.0	5.6
9.001	93-97	c	348	29481	309.6	287.7	138.6	429.0	398.7	4.5	4.1	6.4	6.0	8.6	8.0	12.9	12.0
9.002	93-97	c	348	29481	309.6	287.7	232.2	718.8	668.0	7.5	6.9	10.8	10.0	14.4	13.4	21.6	20.0
9.010	93-97	c	348	29481	309.6	287.7	26.3	81.4	75.6	0.8	0.8	1.2	1.1	1.6	1.5	2.4	2.3
9.011	93-97	c	348	29481	309.6	287.7	5.6	17.2	16.0	0.2	0.2	0.3	0.2	0.3	0.3	0.5	0.5
9.012	93-97	c	348	29481	309.6	287.7	103.1	319.1	296.5	3.3	3.1	4.8	4.4	6.4	5.9	9.6	8.9
10.001	93		5	2984	37.0	28.8	266.1	98.6	76.6	1.0	0.8	1.5	1.1	2.0	1.5	3.0	2.3
10.002	93-97	c	348	29481	309.6	287.7	485.8	1503.8	1397.5	15.6	14.5	22.6	21.0	30.1	27.9	45.1	41.9
10.003	93-97	c	348	29481	309.6	287.7	214.8	665.1	618.0	6.9	6.4	10.0	9.3	13.3	12.4	20.0	18.5
10.004	93-97	c	348	29481	309.6	287.7	74.0	229.2	213.0	2.4	2.2	3.4	3.2	4.6	4.3	6.9	6.4
105.001	97	b	57	6328	469.1	397.5	50.3	236.1	200.0	2.5	2.1	3.5	3.0	4.7	4.0	7.1	6.0
105.002	97	b	57	6328	469.1	397.5	6.6	30.8	26.1	0.3	0.3	0.5	0.4	0.6	0.5	0.9	0.8
106.002	94		28	2633	783.4	598.0	1827.9	14319.7	10931.1	148.9	113.7	214.8	164.0	286.4	218.6	429.6	327.9
					N. Coast	Total	50205.2	242951.9	173846.6	2526.7	1808.0	3644.3	2607.7	4859.0	3476.9	7288.6	5215.4
South Coast of British Columbia																	
11.001	96	d	31	1339	573.4	383.1	135.9	779.1	520.6	8.1	5.4	11.7	7.8	15.6	10.4	23.4	15.6

PMF Subarea	Year	NB	Transect		Biomass (g/m^2)		Bed area (ha)	Bc Biomass (t)		Quota 0.2 M Bc (of urchins 100-140 mm TD)							
										M = 0.052		M = 0.075		M = 0.10		M = 0.15	
			No	Length (m)	Mean	Lower 90 % CI	1996	Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI
11.002	96		31	1339	573.4	383.1	142.6	817.9	546.5	8.5	5.7	12.3	8.2	16.4	10.9	24.5	16.4
12.001	99		13	627	232.2	119.6	61.6	143.0	73.7	1.5	0.8	2.1	1.1	2.9	1.5	4.3	2.2
12.002	99		16	830	147.4	85.3	96.5	142.3	82.3	1.5	0.9	2.1	1.2	2.8	1.6	4.3	2.5
12.003	94		9	309	704.1	217.7	180.6	1271.6	393.2	13.2	4.1	19.1	5.9	25.4	7.9	38.1	11.8
12.004	94		1	25	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.005	94		9	381	522.2	197.4	143.2	747.8	282.6	7.8	2.9	11.2	4.2	15.0	5.7	22.4	8.5
12.006	94		14	1292	124.1	82.2	146.1	181.3	120.0	1.9	1.2	2.7	1.8	3.6	2.4	5.4	3.6
12.007	95		6	225	742.9	141.5	73.5	545.9	104.0	5.7	1.1	8.2	1.6	10.9	2.1	16.4	3.1
12.008	94		3	280	57.1	15.7	93.0	53.1	14.6	0.6	0.2	0.8	0.2	1.1	0.3	1.6	0.4
12.011	94		15	713	688.8	375.6	239.4	1648.9	899.1	17.1	9.4	24.7	13.5	33.0	18.0	49.5	27.0
12.012	94		2	69	849.3	0.0	172.6	1465.9	0.0	15.2	0.0	22.0	0.0	29.3	0.0	44.0	0.0
12.013	95-96	a	31	1613	601.2	419.4	117.3	705.4	492.1	7.3	5.1	10.6	7.4	14.1	9.8	21.2	14.8
12.014	96		6	609	489.0	248.4	425.3	2079.8	1056.5	21.6	11.0	31.2	15.8	41.6	21.1	62.4	31.7
12.015	94		2	57	1051.2	0.0	27.6	289.7	0.0	3.0	0.0	4.3	0.0	5.8	0.0	8.7	0.0
12.016	94		18	1488	475.5	325.8	303.7	1444.1	989.6	15.0	10.3	21.7	14.8	28.9	19.8	43.3	29.7
12.017	94		2	443	0.0	0.0	39.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.018	94		18	982	477.2	292.3	350.0	1670.3	1023.1	17.4	10.6	25.1	15.3	33.4	20.5	50.1	30.7
12.019	94		3	258	88.2	21.5	65.7	57.9	14.1	0.6	0.1	0.9	0.2	1.2	0.3	1.7	0.4
12.020	94		1	59	1087.4	0.0	1.4	15.2	0.0	0.2	0.0	0.2	0.0	0.3	0.0	0.5	0.0
12.021	94		2	93	933.9	0.0	17.6	164.7	0.0	1.7	0.0	2.5	0.0	3.3	0.0	4.9	0.0
12.024	99		2	72	233.8	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.026	94-96	b	170	10215	378.1	332.7	4.0	15.0	13.2	0.2	0.1	0.2	0.2	0.3	0.3	0.4	0.4
12.036	94		1	83	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.039	94-95	a	24	1579	38.8	26.9	59.8	23.2	16.1	0.2	0.2	0.3	0.2	0.5	0.3	0.7	0.5
12.041	95		7	194	436.8	56.0	86.8	379.0	48.6	3.9	0.5	5.7	0.7	7.6	1.0	11.4	1.5
12.042	94-96	b	170	10215	378.1	332.7	18.0	68.1	59.9	0.7	0.6	1.0	0.9	1.4	1.2	2.0	1.8
13.001	99	b	43	2041	552.5	404.0	170.2	940.5	687.7	9.8	7.2	14.1	10.3	18.8	13.8	28.2	20.6
13.002	99	b	43	2041	552.5	404.0	74.7	412.6	301.7	4.3	3.1	6.2	4.5	8.3	6.0	12.4	9.1
13.003	99	b	43	2041	552.5	404.0	40.7	225.0	164.5	2.3	1.7	3.4	2.5	4.5	3.3	6.7	4.9
13.006	99	b	43	2041	552.5	404.0	60.8	336.1	245.8	3.5	2.6	5.0	3.7	6.7	4.9	10.1	7.4
13.007	99	b	43	2041	552.5	404.0	51.1	282.2	206.4	2.9	2.1	4.2	3.1	5.6	4.1	8.5	6.2
13.008	99	b	43	2041	552.5	404.0	8.4	46.6	34.1	0.5	0.4	0.7	0.5	0.9	0.7	1.4	1.0
13.009	99	b	43	2041	552.5	404.0	19.3	106.7	78.0	1.1	0.8	1.6	1.2	2.1	1.6	3.2	2.3
13.010	99	b	43	2041	552.5	404.0	72.3	399.5	292.2	4.2	3.0	6.0	4.4	8.0	5.8	12.0	8.8

PMF Subarea	Year	NB	Transect		Biomass (g/m^2)		Bed area (ha)	Bc Biomass (t)		Quota 0.2 M Bc (of urchins 100-140 mm TD)							
										M = 0.052		M = 0.075		M = 0.10		M = 0.15	
			No	Length (m)	Mean	Lower 90 % CI	1996	Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI
13.011	99	b	43	2041	552.5	404.0	28.8	159.3	116.5	1.7	1.2	2.4	1.7	3.2	2.3	4.8	3.5
13.012	99	b	43	2041	552.5	404.0	142.1	785.2	574.1	8.2	6.0	11.8	8.6	15.7	11.5	23.6	17.2
13.016	99	b	43	2041	552.5	404.0	14.9	82.2	60.1	0.9	0.6	1.2	0.9	1.6	1.2	2.5	1.8
13.017	99	b	43	2041	552.5	404.0	8.9	49.3	36.0	0.5	0.4	0.7	0.5	1.0	0.7	1.5	1.1
13.023	99	b	43	2041	552.5	404.0	66.1	365.3	267.1	3.8	2.8	5.5	4.0	7.3	5.3	11.0	8.0
13.025	99	b	43	2041	552.5	404.0	107.6	594.5	434.7	6.2	4.5	8.9	6.5	11.9	8.7	17.8	13.0
13.026	99	b	43	2041	552.5	404.0	30.5	168.4	123.1	1.8	1.3	2.5	1.8	3.4	2.5	5.1	3.7
13.027	99	b	43	2041	552.5	404.0	31.0	171.5	125.4	1.8	1.3	2.6	1.9	3.4	2.5	5.1	3.8
13.028	99	b	43	2041	552.5	404.0	152.1	840.2	614.4	8.7	6.4	12.6	9.2	16.8	12.3	25.2	18.4
13.029	99	b	43	2041	552.5	404.0	17.6	97.0	70.9	1.0	0.7	1.5	1.1	1.9	1.4	2.9	2.1
13.030	99		4	162	139.6	6.4	84.1	117.4	5.4	1.2	0.1	1.8	0.1	2.3	0.1	3.5	0.2
13.031	99		5	229	715.4	141.4	29.1	208.3	41.2	2.2	0.4	3.1	0.6	4.2	0.8	6.2	1.2
13.032	99		18	868	606.2	356.4	165.0	1000.0	587.9	10.4	6.1	15.0	8.8	20.0	11.8	30.0	17.6
13.033	99		7	463	717.0	312.4	53.2	381.5	166.2	4.0	1.7	5.7	2.5	7.6	3.3	11.4	5.0
13.035	99		9	319	260.0	83.3	71.9	187.0	59.9	1.9	0.6	2.8	0.9	3.7	1.2	5.6	1.8
13.036	99	b	43	2041	552.5	404.0	46.1	254.6	186.2	2.6	1.9	3.8	2.8	5.1	3.7	7.6	5.6
13.039	99	b	43	2041	552.5	404.0	62.6	345.8	252.9	3.6	2.6	5.2	3.8	6.9	5.1	10.4	7.6
13.040	99	b	43	2041	552.5	404.0	23.3	128.8	94.2	1.3	1.0	1.9	1.4	2.6	1.9	3.9	2.8
13.041	99	b	43	2041	552.5	404.0	18.7	103.2	75.5	1.1	0.8	1.5	1.1	2.1	1.5	3.1	2.3
14.005	99		2	202	104.6	15.2		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14.007	99		9	1383	134.4	90.5	79.9	107.4	72.3	1.1	0.8	1.6	1.1	2.1	1.4	3.2	2.2
14.008	99		6	812	215.7	123.8	22.0	47.4	27.2	0.5	0.3	0.7	0.4	0.9	0.5	1.4	0.8
14.009	99		22	3776	115.4	92.6	205.4	236.9	190.1	2.5	2.0	3.6	2.9	4.7	3.8	7.1	5.7
14.010	99	b	61	8391	110.0	95.5	226.0	248.7	215.7	2.6	2.2	3.7	3.2	5.0	4.3	7.5	6.5
14.011	99		17	1715	40.9	28.9	75.9	31.1	22.0	0.3	0.2	0.5	0.3	0.6	0.4	0.9	0.7
14.012	99		5	503	70.4	32.3	55.8	39.3	18.0	0.4	0.2	0.6	0.3	0.8	0.4	1.2	0.5
14.013	99	b	61	8391	110.0	95.5	182.3	200.6	174.0	2.1	1.8	3.0	2.6	4.0	3.5	6.0	5.2
15.001	99	e	61	8391	110.0	95.5	6.7	7.4	6.4	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2
15.002	99	e	61	8391	110.0	95.5	25.8	28.4	24.6	0.3	0.3	0.4	0.4	0.6	0.5	0.9	0.7
15.004	99	e	61	8391	110.0	95.5	4.4	4.9	4.2	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1
17.001	98		4	232	32.8	6.6	1.2	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17.002	98		3	231	6.4	1.3	65.8	4.2	0.8	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0
17.003	98-99	f	74	3570	111.8	89.0	69.7	77.9	62.1	0.8	0.6	1.2	0.9	1.6	1.2	2.3	1.9
17.008	98-99	f	74	3570	111.8	89.0	30.1	33.6	26.8	0.3	0.3	0.5	0.4	0.7	0.5	1.0	0.8

PMF Subarea	Year	NB	Transect No	Transect Length (m)	Biomass (g/m^2) Mean	Biomass (g/m^2) Lower 90 % CI	Bed area (ha) 1996	Bc Biomass (t) Mean	Bc Biomass (t) Lower 90 % CI	Quota 0.2 M Bc (of urchins 100-140 mm TD) M = 0.052 Mean	M = 0.052 Lower 90 % CI	M = 0.075 Mean	M = 0.075 Lower 90 % CI	M = 0.10 Mean	M = 0.10 Lower 90 % CI	M = 0.15 Mean	M = 0.15 Lower 90 % CI
17.010	98-99	f	74	3570	111.8	89.0	40.0	44.7	35.7	0.5	0.4	0.7	0.5	0.9	0.7	1.3	1.1
17.012	98-99	f	74	3570	111.8	89.0	4.0	4.5	3.6	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1
17.017	98-99	f	74	3570	111.8	89.0	8.1	9.1	7.2	0.1	0.1	0.1	0.1	0.2	0.1	0.3	0.2
18.001	98		6	366	73.4	26.8	89.8	66.0	24.1	0.7	0.3	1.0	0.4	1.3	0.5	2.0	0.7
18.002	98		8	356	80.7	28.8	131.6	106.2	37.8	1.1	0.4	1.6	0.6	2.1	0.8	3.2	1.1
18.003	98		11	677	11.4	6.1	53.8	6.1	3.3	0.1	0.0	0.1	0.0	0.1	0.1	0.2	0.1
18.004	99		8	576	60.7	30.0	66.8	40.6	20.1	0.4	0.2	0.6	0.3	0.8	0.4	1.2	0.6
18.005	99		6	460	86.5	37.5	67.5	58.4	25.3	0.6	0.3	0.9	0.4	1.2	0.5	1.8	0.8
18.006	99		22	2706	150.3	115.2	181.3	272.4	208.8	2.8	2.2	4.1	3.1	5.4	4.2	8.2	6.3
18.007	98-99	b	74	3570	111.8	89.0	19.4	21.6	17.2	0.2	0.2	0.3	0.3	0.4	0.3	0.6	0.5
18.009	98		1	45	0.0	0.0	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18.011	98		4	176	309.8	26.2	54.9	170.2	14.4	1.8	0.1	2.6	0.2	3.4	0.3	5.1	0.4
19.004	98-99	f	74	3570	111.8	89.0	29.5	32.9	26.2	0.3	0.3	0.5	0.4	0.7	0.5	1.0	0.8
19.005	98-99	f	74	3570	111.8	89.0	215.9	241.3	192.3	2.5	2.0	3.6	2.9	4.8	3.8	7.2	5.8
20.003	74-85	g			589.0	362.8	294.2	1732.6	1067.3	18.0	11.1	26.0	16.0	34.7	21.3	52.0	32.0
20.005	74-85	g			589.0	362.8	172.5	1016.1	626.0	10.6	6.5	15.2	9.4	20.3	12.5	30.5	18.8
20.006	74-85	g			589.0	362.8	32.5	191.5	118.0	2.0	1.2	2.9	1.8	3.8	2.4	5.7	3.5
23.005	74-85	g			589.0	362.8	52.9	311.5	191.9	3.2	2.0	4.7	2.9	6.2	3.8	9.3	5.8
23.007	74-85	g			589.0	362.8	64.2	378.4	233.1	3.9	2.4	5.7	3.5	7.6	4.7	11.4	7.0
23.009	74-85	g			589.0	362.8	6.9	40.8	25.1	0.4	0.3	0.6	0.4	0.8	0.5	1.2	0.8
23.011	74-85	g			589.0	362.8	132.6	781.0	481.1	8.1	5.0	11.7	7.2	15.6	9.6	23.4	14.4
24.002	74-85	g			589.0	362.8	88.4	520.7	320.7	5.4	3.3	7.8	4.8	10.4	6.4	15.6	9.6
24.006	74-85	g			589.0	362.8	452.5	2665.1	1641.8	27.7	17.1	40.0	24.6	53.3	32.8	80.0	49.3
24.007	74-85	g			589.0	362.8	97.5	574.4	353.8	6.0	3.7	8.6	5.3	11.5	7.1	17.2	10.6
24.008	74-85	g			589.0	362.8	153.9	906.4	558.3	9.4	5.8	13.6	8.4	18.1	11.2	27.2	16.7
24.009	74-85	g			589.0	362.8	7.0	41.2	25.4	0.4	0.3	0.6	0.4	0.8	0.5	1.2	0.8
25.006	74-85	g			589.0	362.8	70.3	414.2	255.1	4.3	2.7	6.2	3.8	8.3	5.1	12.4	7.7
25.007	74-85	g			589.0	362.8	193.4	1139.4	701.9	11.8	7.3	17.1	10.5	22.8	14.0	34.2	21.1
25.013	74-85	g			589.0	362.8	297.4	1751.7	1079.1	18.2	11.2	26.3	16.2	35.0	21.6	52.6	32.4
25.015	74-85	g			589.0	362.8	41.4	244.1	150.4	2.5	1.6	3.7	2.3	4.9	3.0	7.3	4.5
26.001	74-85	g			589.0	362.8	12.1	71.4	44.0	0.7	0.5	1.1	0.7	1.4	0.9	2.1	1.3
26.006	74-85	g			589.0	362.8	25.7	151.3	93.2	1.6	1.0	2.3	1.4	3.0	1.9	4.5	2.8
27.001	74-85	g			589.0	362.8	29.4	173.4	106.8	1.8	1.1	2.6	1.6	3.5	2.1	5.2	3.2
27.002	74-85	g			589.0	362.8	268.4	1581.1	974.0	16.4	10.1	23.7	14.6	31.6	19.5	47.4	29.2

PMF Subarea	Year	NB	Transect No	Transect Length (m)	Biomass (g/m^2) Mean	Biomass (g/m^2) Lower 90 % CI	Bed area (ha) 1996	Bc Biomass (t) Mean	Bc Biomass (t) Lower 90 % CI	Quota 0.2 M Bc (of urchins 100-140 mm TD) M = 0.052 Mean	M = 0.052 Lower 90 % CI	M = 0.075 Mean	M = 0.075 Lower 90 % CI	M = 0.10 Mean	M = 0.10 Lower 90 % CI	M = 0.15 Mean	M = 0.15 Lower 90 % CI
27.003	74-85	g			589.0	362.8	42.1	248.1	152.8	2.6	1.6	3.7	2.3	5.0	3.1	7.4	4.6
27.005	74-85	g			589.0	362.8	21.8	128.2	79.0	1.3	0.8	1.9	1.2	2.6	1.6	3.8	2.4
27.007	74-85	g			589.0	362.8	46.2	271.9	167.5	2.8	1.7	4.1	2.5	5.4	3.3	8.2	5.0
27.009	74-85	g			589.0	362.8	59.1	348.0	214.4	3.6	2.2	5.2	3.2	7.0	4.3	10.4	6.4
28.001	74-85	g			589.0	362.8	6.5	38.2	23.5	0.4	0.2	0.6	0.4	0.8	0.5	1.1	0.7
29.002	74-85	g			589.0	362.8	1.1	6.6	4.1	0.1	0.0	0.1	0.1	0.1	0.1	0.2	0.1
29.003	74-85	g			589.0	362.8	3.8	22.6	13.9	0.2	0.1	0.3	0.2	0.5	0.3	0.7	0.4
29.004	74-85	g			589.0	362.8	23.8	140.2	86.4	1.5	0.9	2.1	1.3	2.8	1.7	4.2	2.6
29.005	74-85	g			589.0	362.8	35.5	209.0	128.7	2.2	1.3	3.1	1.9	4.2	2.6	6.3	3.9
111.000	96		6	598	869.2	437.6	205.4	1785.4	898.9	18.6	9.3	26.8	13.5	35.7	18.0	53.6	27.0
124.003	74-85	g			589.0	362.8	2.8	16.3	10.0	0.2	0.1	0.2	0.2	0.3	0.2	0.5	0.3
125.001	74-85	g			589.0	362.8	54.9	323.5	199.3	3.4	2.1	4.9	3.0	6.5	4.0	9.7	6.0
					S. Coast	Total	9669.2	43864.2	25137.4	456.2	261.4	658.0	377.1	877.3	502.7	1315.9	754.1
					B.C.	Total	59874.3	286816.1	198984.0	2982.9	2069.4	4302.2	2984.8	5736.3	3979.7	8604.5	5969.5

Table 7. Total quota (tonnes) options for the red sea urchin fishery by north and south B.C., estimated from various natural mortality values applied to current biomass (Bc) calculated from mean and approximate 90% lower confidence interval (CI) biomassvalues for five size limits of commercial red sea urchin, and bed areas fished up to 1996.

Size Limit (mm TD)	Region	Quota 0.2 M Bc							
		M = 0.052		M = 0.075		M = 0.10		M = 0.15	
		Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI	Mean	Lower 90 % CI
≥100	North Coast	2869.4	2084.3	4138.5	3006.3	5518.0	4008.3	8277.0	6012.5
	South Coast	556.5	322.6	802.7	465.3	1070.3	620.4	1605.4	930.6
	B.C.	3425.9	2407.0	4941.2	3471.6	6588.3	4628.8	9882.4	6943.1
100-140	North Coast	2526.7	1808.0	3644.3	2607.7	4859.0	3476.9	7288.6	5215.4
	South Coast	456.2	261.4	658.0	377.1	877.3	502.7	1315.9	754.1
	B.C.	2982.9	2069.4	4302.2	2984.8	5736.3	3979.7	8604.5	5969.5
≥90	North Coast	3359.5	2457.7	4845.4	3544.7	6460.6	4726.3	9690.9	7089.5
	South Coast	628.7	370.6	906.8	534.5	1209.0	712.7	1813.6	1069.0
	B.C.	3988.2	2828.3	5752.2	4079.2	7669.6	5439.0	11504.4	8158.5
90-120	North Coast	2018.5	1480.1	2911.4	2134.7	3881.8	2846.3	5822.7	4269.4
	South Coast	311.2	188.0	448.8	271.2	598.4	361.6	897.7	542.4
	B.C.	2329.7	1668.1	3360.2	2405.9	4480.3	3207.9	6720.4	4811.8
90-130	North Coast	2589.3	1906.8	3734.5	2750.2	4979.4	3667.0	7469.1	5500.4
	South Coast	419.1	253.9	604.4	366.1	805.9	488.2	1208.8	732.3
	B.C.	3008.3	2160.7	4338.9	3116.4	5785.2	4155.1	8677.9	6232.7

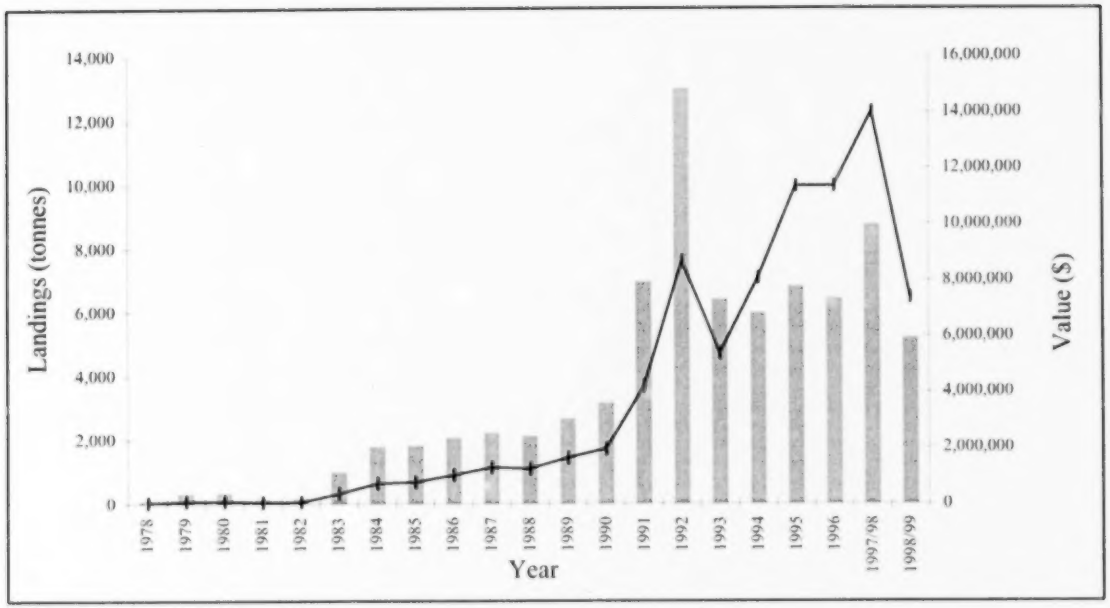

Fig. 1. Annual yield (columns) and value (diamond/line) for the red sea urchin fishery in British Columbia, 1978-99.

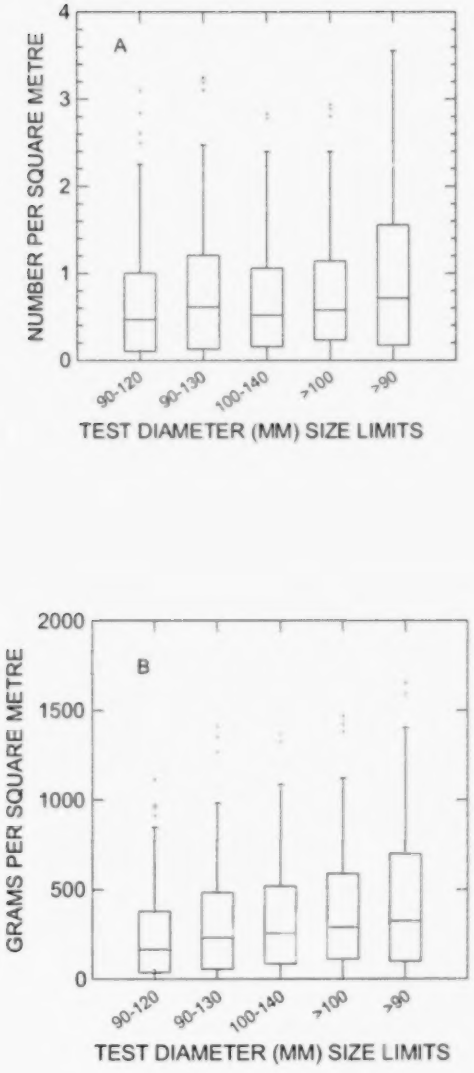

Fig. 2. Box plots of mean (A) density and (B) biomass for different size limits ($\geq$ 100, $\geq$90, 100-140, 90-120, and 90-130 mm TD) calculated from surveys of red sea urchin populations in different PFM subareas throughout B.C., during 1993-99 (N = 129). The horizontal central line of a box plot is the median and the two horizontal outer lines are the first and third quantiles of the sample, and the asterisks are outliers.

APPENDIX A
PRELIMINARY PROBABILISTIC MODELING OF THE EFFECTS OF HARVEST-RATES AND SIZE-RESTRICTIONS ON A POPULATION OF RED SEA URCHINS (*Strongylocentrotus franciscanus*)

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Introduction

The long-term impact of various harvesting strategies are estimated using a computer program to simulate the dynamics of a population of red sea urchins (*Strongylocentrotus franciscanus*). The expected behaviours of the population are expressed as mathematical equations and combined into a computer model. A set of parameter values is identified that allows the model to reach an equilibrium state that is similar to results of a size-frequency survey of an urchin bed. Random variability of environmental factors is introduced into the model to allow a probabilistic assessment of various strategies for the harvest of red sea urchins.

There are many other models of red sea urchins and other marine invertebrates (Lai and Bradbury 1998 and Breen and Kendrick 1998 for example). The analyses in this report are unique in two respects:

1. The values of independent parameters are chosen such that the model predicts that in a constant environment with no harvesting, the stock will remain stable in it's virgin state. The more common approach is to determine a history of the parameter values that could lead to the present state of the population.
2. The growth of the urchins is determined by both their biological potential for growth and by the capacity of the local environment to support growth. The more common approach is to only consider the biological capacity for growth.

Sample data is analyzed to demonstrate how the impact of harvesting can be predicted from the exploitation rate (fraction of harvestable animals taken each year) and an estimate of the virgin-state of the stock.

An Equilibrium Approach to Population Modelling

The model for a red sea urchin (RSU) population is based on the concept of an equilibrium state. In an equilibrium state, environmental conditions and harvesting strategies are held constant and consequently the characteristics of the RSU population (number of animals, biomass, etc.) also reach a constant state. A set of parameter values is identified for the model that lead to a predicted steady-state that is similar to the results of a size-frequency survey of a virgin stock. Further analysis is based on variants of this equilibrium.

From a population-modeling perspective, RSU have four significant activities:

1. Settlement

2.G rowth
3.Mo rtality
4.S pat production

Because there is equilibrium, the rate of settlement can be determined from the survival rate and the number of animals. Estimated survival rates for RSU on the west coast of Canada typically range from 0.85 to 0.97 (A.Campbell, unpublished data). For the purpose of example, a survival rate of S_{urv}=0.9 will be used. In order to maintain an equilibrium population of P_{equib}, the settlement rate must be $S_{ettle}=P_{equib}*(1/S_{urv}-1)$ spats per year. When the survival rate is applied to the population including the new spats, the resulting number of RSU is $S_{urv}*(P_{equib}+S_{ettle})=P_{equib}$.

Similarly, the equilibrium growth rate can be determined from the survival rate and the biomass. If an equilibrium biomass of B_{equib} is to be maintained, then the amount of growth that occurs every year is $G_{rowth}=B_{equib}*(1/S_{urv}-1)$ grams per year. When the survival rate is applied after growth has occurred, the resulting biomass is $S_{urv}*(B_{equib}+G_{rowth})=B_{equib}$.

If meta-population effects are ignored, then the rate at which spats are produced equals the settlement rate.

Figure A1 shows the size frequency density (SFD) taken from a survey of a virgin (or close to it) RSU stock. As often occurs with RSU surveys, the SFD is very discontinuous and therefore the precision is questionable. Even though the actual SFD may not be precisely known, the survey data does have two identifiable characteristics that can serve as useful constraints on the equilibrium state:

- The maximum test diameter of an RSU is approximately 165 mm.
- The SFD is bimodal with peaks at approximately 25 and 125 mm.

These constraints on the equilibrium state are enough to estimate parameter values for the model used in the analysis. A model with more independent parameters would require more constraints on the equilibrium state and consequently be more dependent on the accuracy of survey data.

The Model Equations

Survival

To account for natural mortality, a single survival rate (fraction of RSU to survive a given year), S_{urv}, is applied to all sizes of RSU.

Harvest is represented by a lower size limit, an upper size limit and a fishing rate, f_{rate}. The fishing rate is expressed as the fraction of RSU in the harvestable size-range to be harvested in a year. For RSU within the size limits, the survival rate is $S_{urv}*(1-f_{rate})$. If the biomass falls below 20% of the equilibrium level, the stock is considered to have collapsed and harvest stops. After a stock-collapse, the stock is considered to have recovered when the biomass reaches 50% of the equilibrium level and harvest is resumed.

Growth

An empirical equation is used to describe the growth rate of individual RSU. The equation is based on tagging studies performed on the west coast of Canada (A. Campbell, unpublished data):

$$G(L)=\gamma \cdot e^{-\left(\frac{\zeta-L}{\eta}\right)^2} \cdot \left(1+\varepsilon_{grow}\right)$$

G(L) is the growth rate (mm/year)
L is the current test diameter
γ controls the overall growth rate
ζ and η determine the shape of the curve
ε_{grow} is a Normal variate with a mean of 0 and a standard deviation of σ_{grow}

The growth equation accounts for variability amongst individual animals. As a result, growth of individual RSU can be expressed as the probability of an RSU growing from one test-diameter to another as was done in Lai and Bradbury 1998.

Figure A2 shows a fit of the growth equation to experimental data taken from the Haida Research Area, Site 3 in 1997 (Alan Campbell, unpublished data).

The chosen growth equation has two notable features that make it amenable to calibrating the model to an equilibrium state:

- It is size-based (as opposed to age-based)
- The overall growth rate is controlled by a single parameter, γ.

The value of γ is limited in two ways:

1. The capacity of the local environment to support the growth of RSU (food in particular).
2. The biological potential growth of RSU.

The first limit is especially relevant where growth is food-limited. Studies (Vadas 1977 for example) have suggested that the growth of RSU is often food-limited. The limit is applied by assuming the local environment has potential to support a fixed amount of growth in the RSU biomass. This potential growth is distributed amongst all the RSU in the population. Generally, as this potential growth is divided amongst more RSU, the individual growth rates become smaller. A value of γ can be found (numerical methods) such that the RSU population uses all the potential for growth provided by the local environment.

The second limit is necessary to prevent unrealistically large growth rates when the stock of RSU becomes small. A maximum value of γ is applied. This limit is only significant when the RSU stock becomes small.

Spat Production

Spat production is the combination of several processes and characteristics; fecundity, fertilization success, larval survival and the migration of larvae between sub-populations of a meta-population. For simplicity, the migration of larvae between sub-populations will be ignored while defining the equilibrium state. The local population is assumed to be its own source and destination of spats. Meta-population effects are expected to contribute variability into the settlement rate and this variability will be incorporated into the probabilistic simulations.

A modification of the Ricker curve (Quinn and Deriso, 1997) is used to estimate the settlement rate.

$$S_{ettle}=R_{coef}*B_{mature}*\exp(-B/B_{equib})$$

R_{coef} is a scaling factor and one of the independent parameters of the model
B is the current biomass
B_{equib} is the equilibrium biomass
B_{mature} is the current biomass of mature RSU

At equilibrium:

$$R_{coef} = P_{equib}*(1/S_{urv} -1)/B_{mature.equib}/\exp(-1)$$

$B_{mature.equib}$ is the biomass of mature RSU at equilibrium.

An Example of an Equilibrium State

Data from a survey (Queen Charolette Islands, Site 3, 1998, Dominique Bureau, unpublished data) is used to define an equilibrium state. For simplicity, the population is normalized to unity. The following characteristics are observed from the survey:

- The mean mass per RSU is 233 grams.
- The maximum test diameter is approximately 165 mm.
- The SFD is bimodal with peaks at approximately 25 and 125 mm.

Table A1 is a list of values of model-parameter parameters used for the equilibrium. The values of æ and ç are chosen by trial and error in order to get the desired shape of the SFD. Other parameters of the model are chosen by expert opinion. Figure A3 shows the SFD from the survey and from the predicted equilibrium. Table A2 gives some resulting characteristics of the equilibrium state.

Running the Model Probabilistically

Three model parameters are allowed to vary randomly in the model; survival, growth and settlement rate.

Survival

For the equilibrium state, a survival rate of 0.90 per year is selected. By definition, the survival rate must have a value between zero and one. The survival rate for the probabilistic simulations is assigned a normal distribution with a mean of 0.90 and a standard deviation of 0.0333. The survival rate is greater than one in approximately 0.001% of the years.

Growth

For the equilibrium point, the increase in biomass due to growth (ignore mortality) is 25.889 grams per year. The ecological limit to the rate of growth in the biomass is assigned a normal distribution with a mean of 25.889 and a standard deviation of 25.889/2=12.994. There is a 2.28 % probability of negative growth.

A maximum value of 17 mm/year is arbitrarily applied to γ to reflect biological limitations to the growth rate.

Settlement

Variability is introduced into the settlement rate by assigning a lognormal distribution to the multiplicative coefficient, R_{coef}. A lognormal distribution with a square root of ten is used to generate a sporadic settlement rate (as may occur due to metapopulation effects). An arithmetic mean of R_{coef} =0.00139277 spats/gram/year is chosen because it equals the value in the equilibrium state. To obtain the desired arithmetic mean and geometric standard deviation, a geometric mean of 0.000411595 is assigned to R_{coef}.

There is a 95% probability the value of R_{coef} is between 0.00004 and 0.004.

A Probabilistic Simulation with No Harvest

Figure A4 shows some results when the model is run probabilistically for one thousand years with no harvest. The population starts out at the predicted equilibrium. The necessary random values are chosen according to the assigned probability density functions. The resulting settlement, growth and survival rates are applied to the original SFD to predict the state of the population after one year. Similarly, the first-year results and another set of random parameter values are used to estimate the state of the population in the second year. Subsequently, each year is predicted from the previous year and a new set of random values. A simulation of one thousand years was created in this manner.

The estimated biomass is rather stable in the probabilistic simulation even though the variability of the cumulative growth is significant with respect to the mean.

The variability in the settlement rate has a significant influence on the estimated population and correspondingly the mean mass per RSU.

Incorporating Harvest into the Model

Harvest is incorporated into the model with the goal of making informative comparisons of harvest-strategies. The first step is to generate an appropriate no-harvest case to use as a benchmark when evaluating the harvest strategies.

A no-harvest case consisting of 100 simulations of 100 years is used. Each simulation starts at the predicted equilibrium but different random values are used to predict the evolution of the RSU population over 100 years.

The 100 simulations are repeated with various harvesting strategies, but the same random values are used as in the no-harvest case. For every year or simulation in a harvest-case, there is a corresponding year or simulation in the no-harvest case. All differences between the cases are directly attributable to the differences in the harvesting strategies. As a result, a statistical approach known as pairwise comparisons (Montgomery, 1991) can be used to evaluate harvest strategies. Seventy-two different harvest strategies are considered; all combinations of nine harvest rates and eight harvestable size ranges.

Figure A5 illustrates how a case with harvesting can be compared to the no-harvest case. The mean biomass for each of the one hundred simulations is shown in both the harvest and no-harvest case; the no-harvest case on the x-axis and the harvest-case on the y-axis. A diagonal line is included to show where the points would be if the harvest had no influence on the estimated biomass. The vertical distance between the diagonal line and the points indicates the drop in biomass due to harvesting.

For the harvest strategy used for Figure A5, the long-term influence of harvesting is to cause the biomass to drop by approximately 25 grams or 25/233*100=11% of the equilibrium biomass. The influence of the harvest is easily discernable (visually or quantitatively) even though it is small relative to the variability of the estimated mean biomass.

Results of the Probabilistic Cases

Tables A3-6 show how the various harvesting strategies impact various characteristics of the population. Figures A6-8 show the same information graphically. As expected:

- Smaller harvest rates have smaller impacts on the RSU population
- For the same harvest rate, narrow harvestable ranges result in smaller impacts on the RSU population.

In order to evaluate different harvest strategies, it is necessary to quantify the ecological costs of the harvest and to establish an acceptable cost. *For discussion purposes only* a harvest strategy will be considered acceptable if the resulting drop in biomass is less than 20%.

An actual fishery is more likely to be managed on the basis of yield (mass of catch per year) than on a harvest rate (fraction of haravestable animals). Therefore it is useful to look at how yield affects the biomass. Unfortunately, constant yields are not considered explicitly in the model. To get an approximation of how a constant yield will affect biomass, the drop in biomass for a

simulation of one hundred years is plotted against the mean yield. Some results are shown in Figure A9. Interesting trends are suggested, *but need to be confirmed by simulations where the yield is held constant.*

> For yields less than 3% of the equilibrium biomass per year, there is little difference between the size ranges considered in these analyses. As a *rough* approximation:
>
> > For every gram per year of RSU that is pulled out of the water, the biomass will decrease by approximately ten grams.
>
> For yields greater than three percent of the equilibrium biomass, the linearity is lost. The damage to the biomass increases at a faster rate.

Using These Analyses

Figure A10 shows how a specific environmental impact (a 20% drop in the long-term biomass) can be traced to a range of yield rates. When the harvest rate (fraction of harvestable animals per year) is held constant, a 20% drop in biomass is associated with a yield of approximately 1.8 to 2.3% of the equilibrium biomass per year. If the yield (mass per year) is held constant, similar results are expected (but need to be confirmed with the appropriate simulations). Given the current information for the data considered, a harvest-quota of 1.8% of the virgin biomass per year appears to be precautionary.

Software Used for the Simulations

Probabilistic Urchin Population Simulator (PUPS) is computer program created to produce the cases for these analyses.

PUPS was developed using an object-oriented approach (Rumbaugh et al., 1991). It is written in ANSI C++. As a result, PUPS is very portable and could be easily adaptable to other population analyses involving RSU or other species.

In order to complete the cases for the analyses, PUPS was run on 12 different computers with either a Windows NT or Windows 95 operating system. The time required to complete 100 simulations of 100 years ranged from 8 to 18 hours. The majority of the computational time was spent determining the correct value of γ to use in the growth equation.

Discussion

The analysis demonstrates how the long-term impact of an RSU fishery can be evaluated with respect to quantitative criteria for the long-term impact on the RSU population. In particular, there appears to be a simple relationship between the mass of RSU harvested every year and the resulting drop in biomass. Unfortunately, a constant yield (mass per year) is not one of the harvest strategies considered in the analysis. Any conclusions about the impact of a constant yield should be verified by further analysis.

The analysis is also an opportunity to try a new approach to selecting values for model parameters. Parameter values are chosen so that the long-term equilibrium state predicted by the model are similar to the results of a survey. The advantages of this approach are that there is less dependence on the accuracy of the survey results and there is the assurance that at the model will make sensible predictions (at least under some conditions). A combination of quantitative and qualitative constraints are applied to the equilibrium-state of the model. The approach to selecting parameter-values is successful but it could be explored further.

The experience gained by performing the analysis leads to the following recommendations for developing the methodology:

- A constant yield (mass per year) should be one of the harvest strategies that is considered. Minor modifications to PUPS would be required.
- A rotational fishery, where harvest only occurs every second or third year should be considered. Minor modifications to PUPS would be required.
- Sensitivity analyses should be performed to compare the influences of the model parameters.
- The approach to selecting parameter-values has demonstrated potential. More investigation is warranted to determine if the approach can be further developed so that values for more model-parameters can be estimated. If more model-parameters can be estimated, then there is the potential to incorporate features such as size-specific mortality and density-dependent fertilization success into PUPS.

Acknowledgments

We would like to thank the people who allowed us the use of their computers to run the probabilistic cases.

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Table A1. Model Parameters for an Equilibrium State.

Parameter	Value in Equilibrium
Survival rate of RSU	0.90
Mean mass in equilibrium state	233 g
Coefficient used to determine settlement rate from biomass	0.0013927 spat/g
The size at which an RSU reaches maturity	70 mm
Annual increase in biomass due to growth	25.8889 g
Size at which maximum growth of test-diameter occurs	55 mm
A small value means that growth is concentrated in a small size-range	60 mm
Standard deviation of size for RSU in the first cohort.	3.53 mm
Standard deviation of growth rate for an RSU. Expressed as a fraction of expected growth rate	0.33
Mean test diameter of RSU in the first cohort	10 mm
Scalar multiplier to convert test-diameter to RSU mass(á)	0.0012659
Power Variable used to convert test-diameter to RSU mass (â)	2.7068

Table A2. Results of the Equilibrium State

Characteristic	Value in Equilibrium
Mature Population	0.4612
Scaling Factor used in the growth equation	8.750 mm/year
Settlement Rate	0.111 spat/year

Table A3. Effect of Harvest on the Predicted Biomass

	Drop in Mean Biomass Due to Harvesting (% of Equilibrium Biomass)							
	Harvestable Range (Test Diameter in mm)							
Harvest Rate	100	90	100-140	90-120	90-130	90-140	90-110	70
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.01	6.86	7.45	4.88	2.65	4.00	5.47	1.55	8.27
0.02	12.86	13.99	9.38	5.19	7.76	10.49	3.07	15.56
0.04	23.01	25.09	10.28	9.98	14.66	19.44	6.00	28.07
0.06	31.41	34.35	24.51	14.46	20.90	27.27	8.81	38.61
0.08	38.59	42.28	30.82	18.66	26.61	34.25	11.52	47.81
0.10	44.88	49.26	36.53	22.64	31.87	40.53	14.14	54.93
0.15	56.17	59.74	48.65	31.73	43.55	53.65	20.35	63.17
0.20	61.29	63.35	56.62	39.98	53.25	60.11	26.17	64.70
0.50	64.95	64.89	64.16	61.41	63.77	65.17	55.78	65.06

Table A4. Effect of Harvest on the Predicted Population

	Drop in Mean Population Due to Harvesting (% of Equilibrium Population)							
	Harvestable Range (Test Diameter in mm)							
Harvest Rate	100	90	100-140	90-120	90-130	90-140	90-110	70
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.01	3.21	3.74	2.46	1.70	2.35	2.97	1.11	4.75
0.02	6.50	7.57	4.96	3.39	4.69	5.98	2.20	9.61
0.04	13.11	15.32	5.72	6.76	9.39	12.06	4.38	19.38
0.06	19.66	23.02	15.10	10.09	14.07	18.14	6.54	28.99
0.08	26.01	30.48	20.16	13.38	18.69	24.17	8.67	38.31
0.10	32.14	37.68	25.18	16.63	23.27	30.06	10.78	45.93
0.15	44.23	49.13	37.19	24.61	34.41	43.70	15.97	55.26
0.20	49.90	53.53	45.84	32.42	44.64	50.85	21.07	57.05
0.50	54.63	55.44	55.01	54.90	57.09	57.24	50.27	57.76

Table A5. Effect of Harvest on the Probability of Stock Collapse

	Probability of Stock Collapse in 100 years							
	Harvestable Range (Test Diameter in mm)							
Harvest Rate	100	90	100-140	90-120	90-130	90-140	90-110	70
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
0.08	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.06
0.10	0.04	0.08	0.00	0.00	0.00	0.02	0.00	0.38
0.15	0.56	0.86	0.07	0.00	0.02	0.21	0.00	1.00
0.20	0.97	1.00	0.61	0.00	0.18	0.92	0.00	1.00
0.50	1.00	1.00	1.00	1.00	1.00	1.00	0.36	1.00

Table A6. Effect of Harvest on Predicted Yield

	Yield (% of Equilibrium Biomass per Year)							
	Harvestable Range (Test Diameter in mm)							
Harvest Rate	100	90	100-140	90-120	90-130	90-140	90-110	70
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.01	0.79	0.85	0.56	0.30	0.45	0.62	0.17	0.93
0.02	1.47	1.58	1.07	0.58	0.87	1.18	0.34	1.73
0.04	2.56	2.75	1.16	1.09	1.61	2.14	0.65	2.97
0.06	3.39	3.61	2.68	1.56	2.25	2.91	0.95	3.83
0.08	4.02	4.24	3.29	1.98	2.79	3.53	1.23	4.38
0.10	4.48	4.65	3.78	2.36	3.25	4.01	1.49	4.64
0.15	5.04	5.00	4.60	3.13	4.07	4.67	2.08	4.70
0.20	5.16	5.03	4.90	3.70	4.47	4.77	2.59	4.66
0.50	5.26	5.12	4.93	4.22	4.44	4.70	3.96	4.78

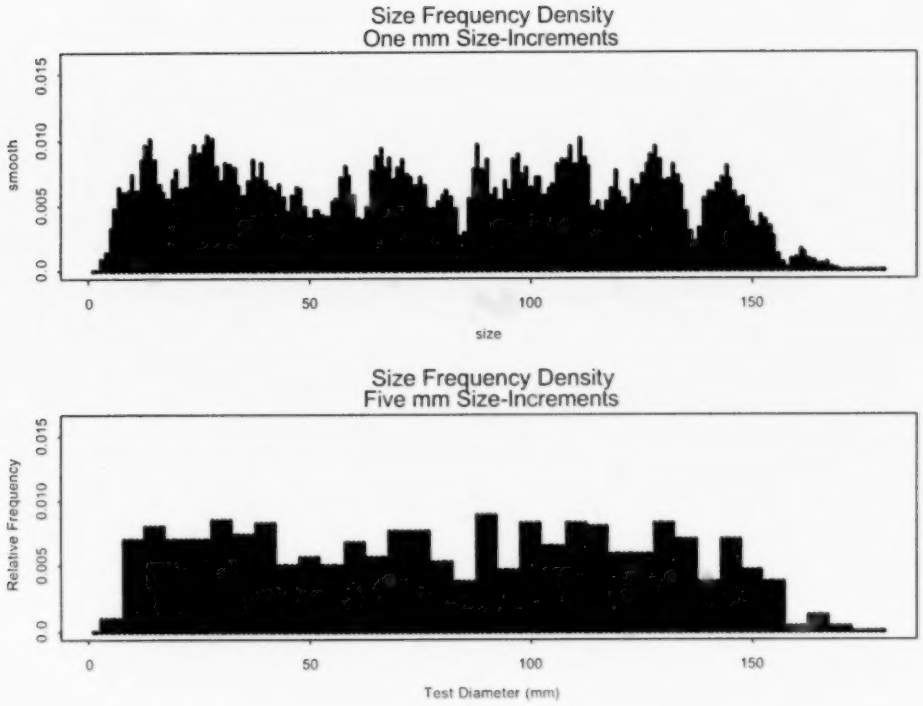

Figure A1. Size Frequency Densities Estimated from Survey Data

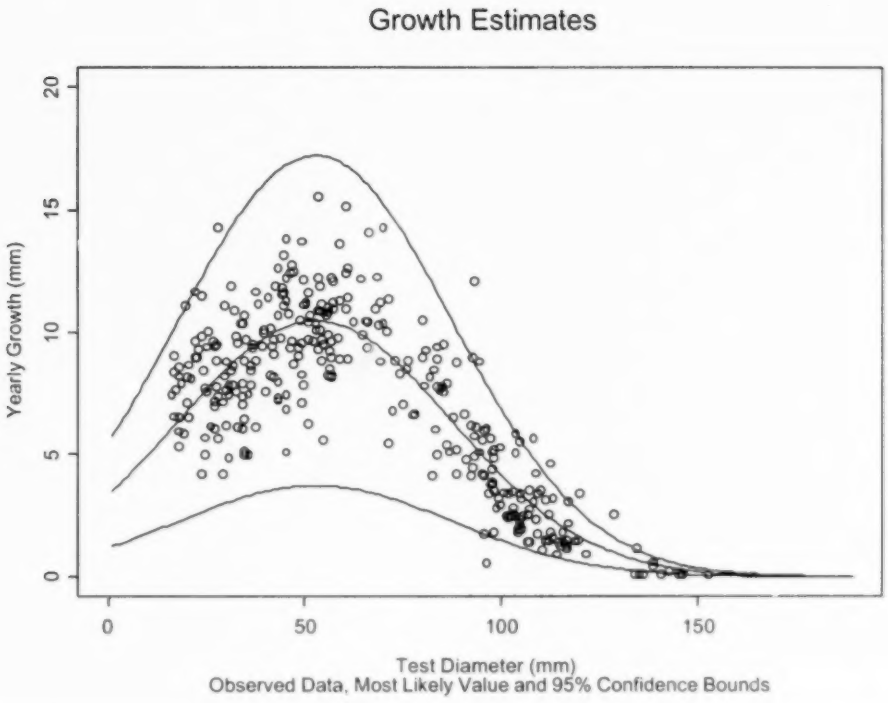

Figure A2. Estimated and Measured Growth Rates. Most Likely Rates and 95% Confidence Bounds are Shown

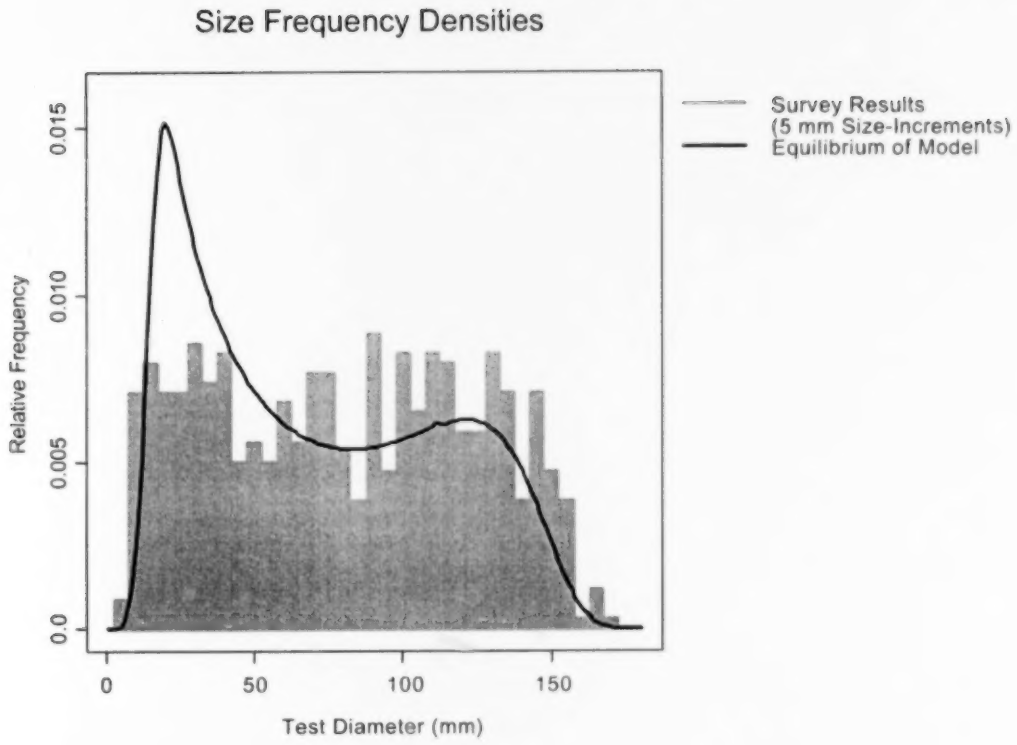

Figure A3. Survey Results and the Equilibrium Estimated by the Model

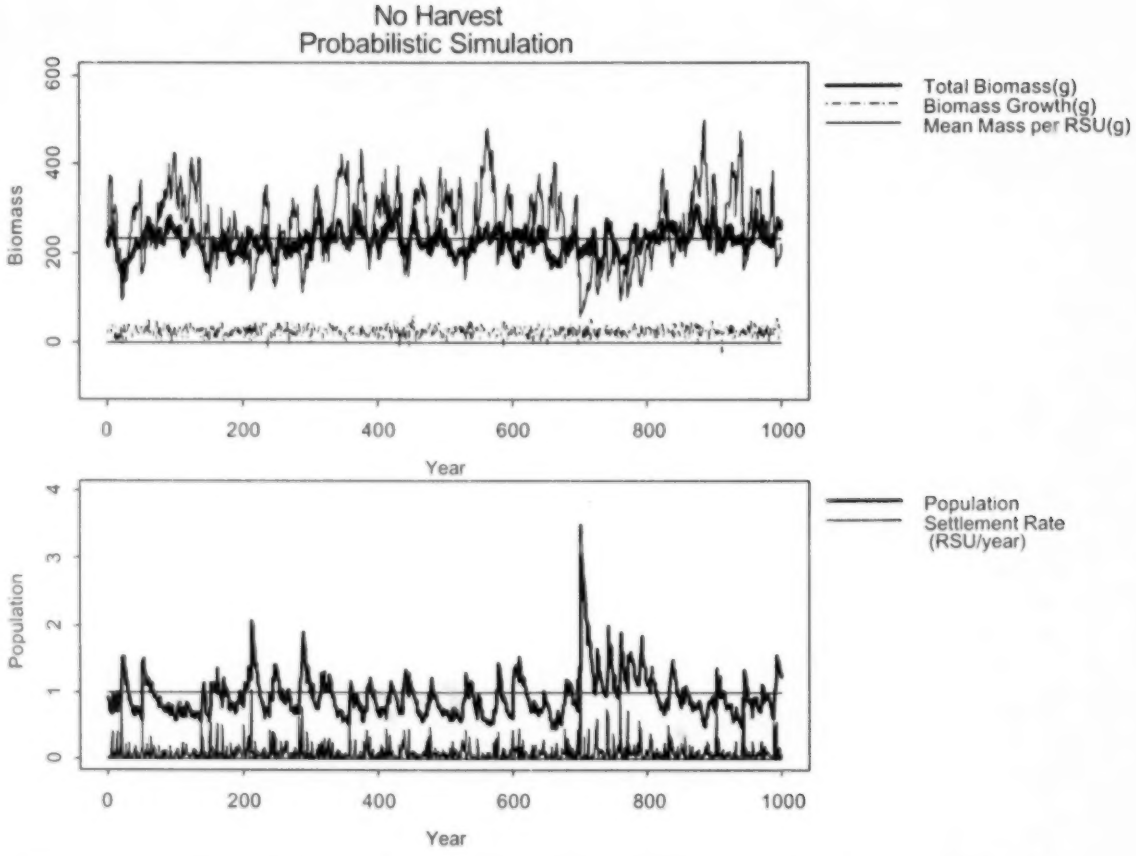

Figure A4. A Probabilistic Simulation with No Harvesting

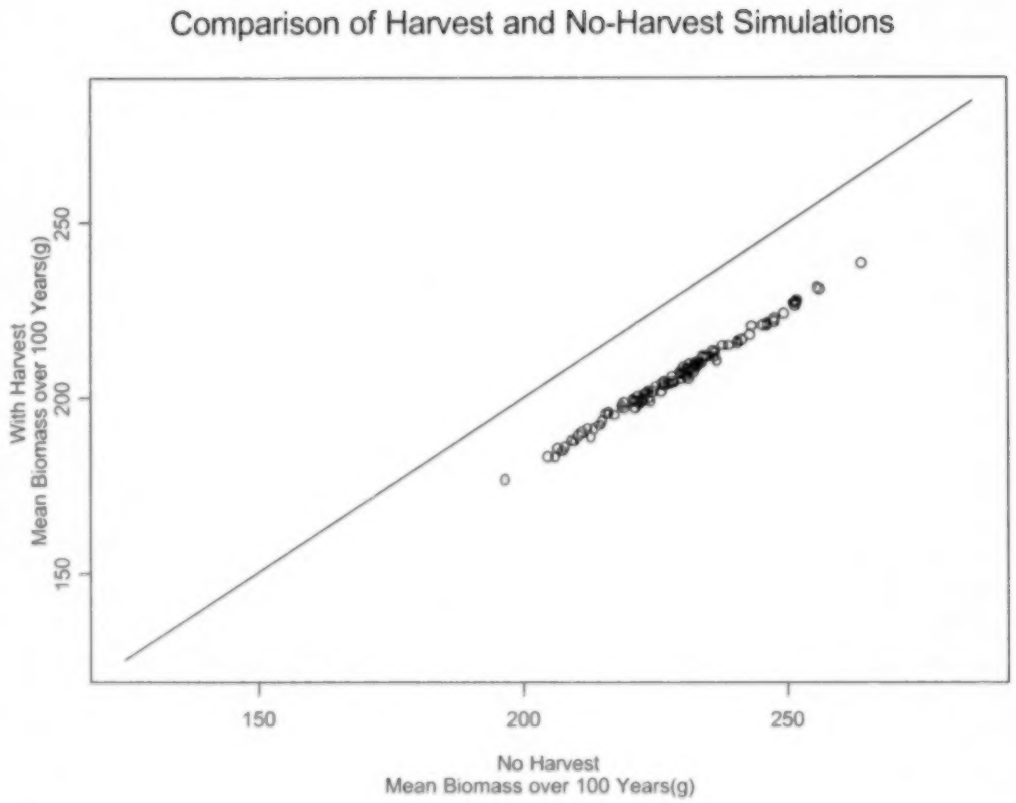

Figure A5. Effect of Harvesting on the Predicted Mean Biomass. A Simulation-by-Simulation Comparison.

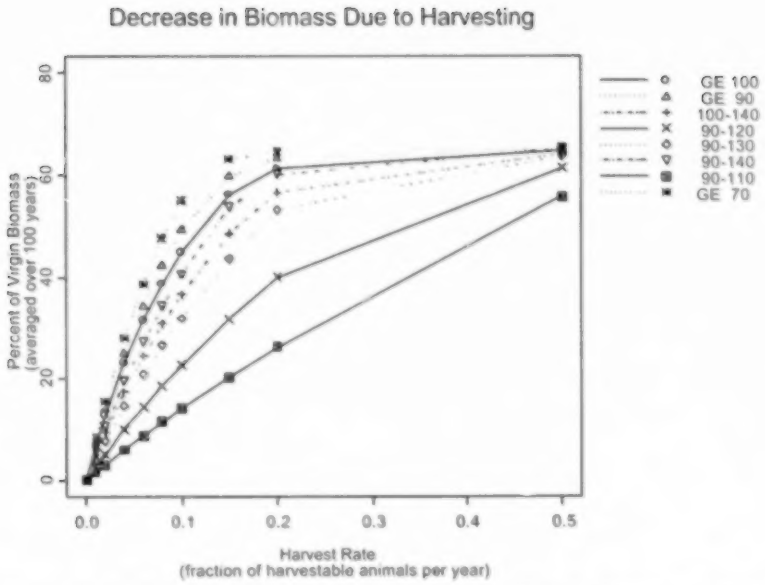

Figure A6 Effect of Harvesting on the Predicted Biomass

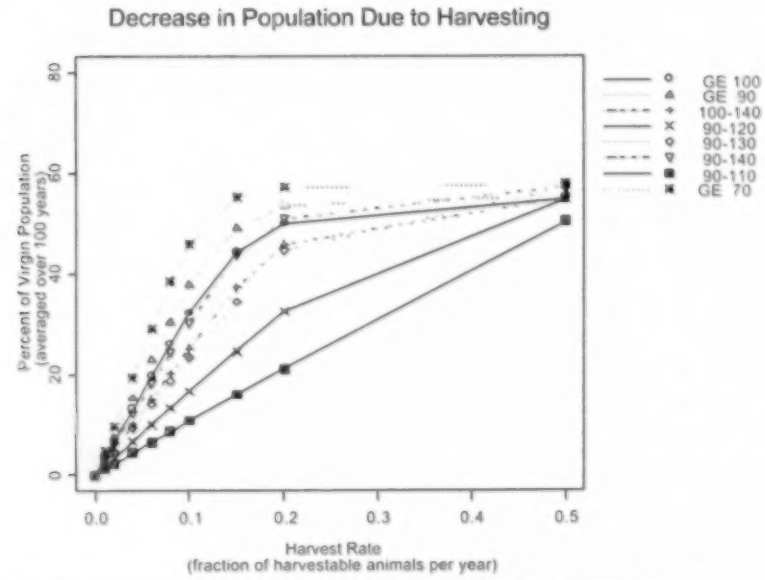

Figure A7 Effect of Harvest on Predicted Population

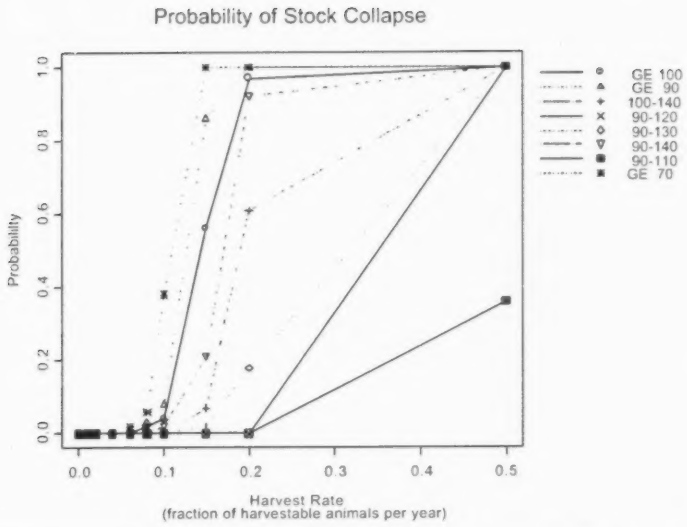

Figure A8 Effect of Harvest on Probability of Stock Collapse

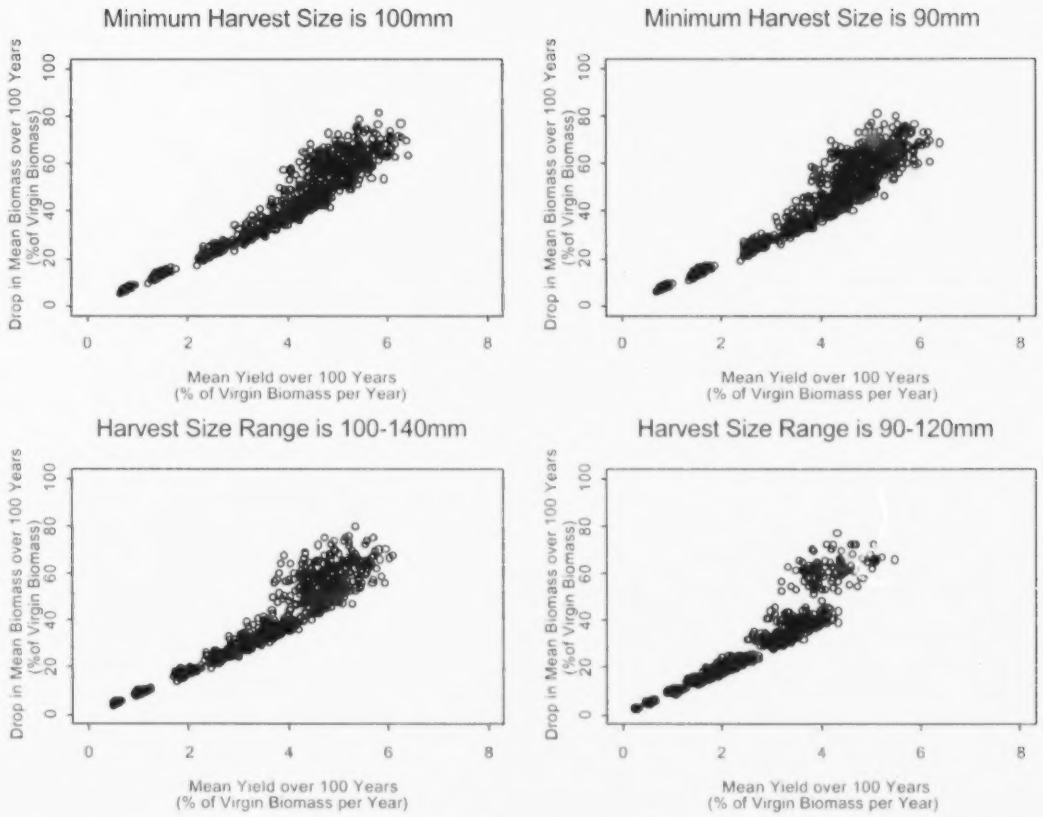

Figure A9. Effect of Yield on Biomass

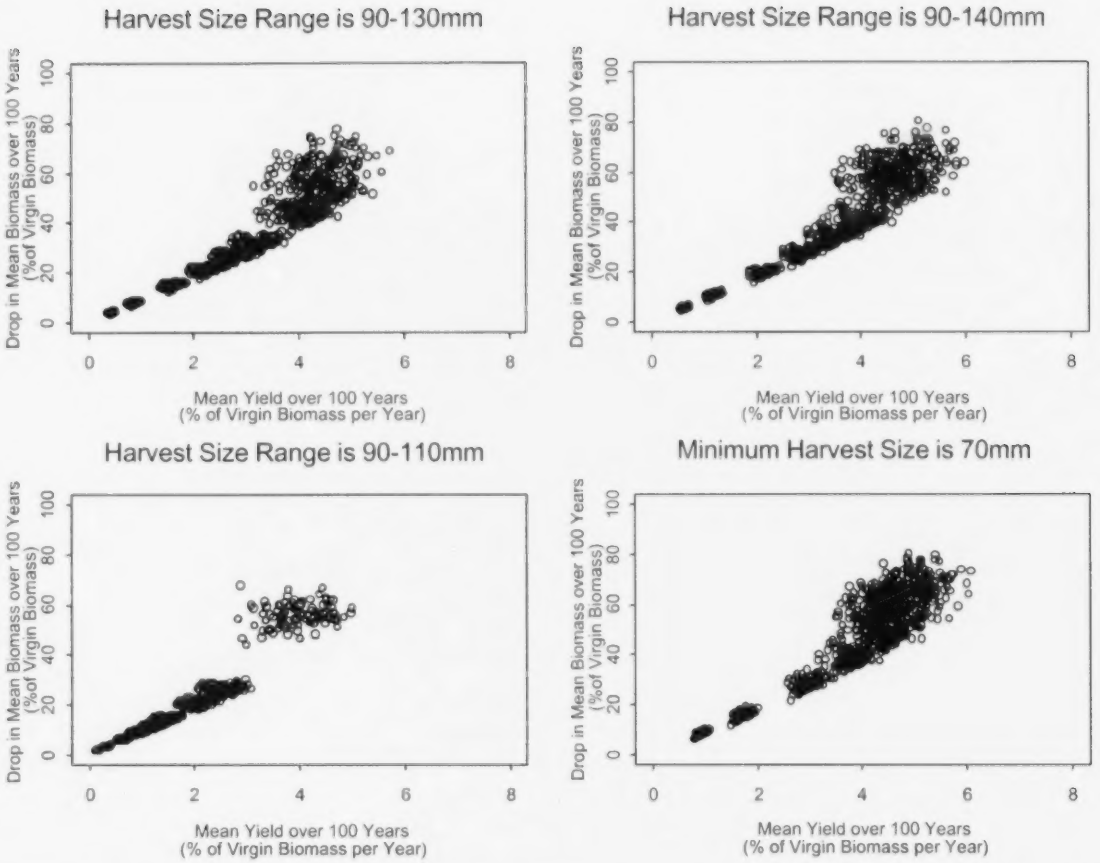
Harvest Size Range is 90-130mm
Drop in Mean Biomass over 100 Years (%of Virgin Biomass)
Mean Yield over 100 Years (% of Virgin Biomass per Year)
Harvest Size Range is 90-140mm
Drop in Mean Biomass over 100 Years (%of Virgin Biomass)
Mean Yield over 100 Years (% of Virgin Biomass per Year)
Harvest Size Range is 90-110mm
Drop in Mean Biomass over 100 Years (%of Virgin Biomass)
Mean Yield over 100 Years (% of Virgin Biomass per Year)
Minimum Harvest Size is 70mm
Drop in Mean Biomass over 100 Years (%of Virgin Biomass)
Mean Yield over 100 Years (% of Virgin Biomass per Year)

Figure A9. Effect of Yield on Biomass (continued)

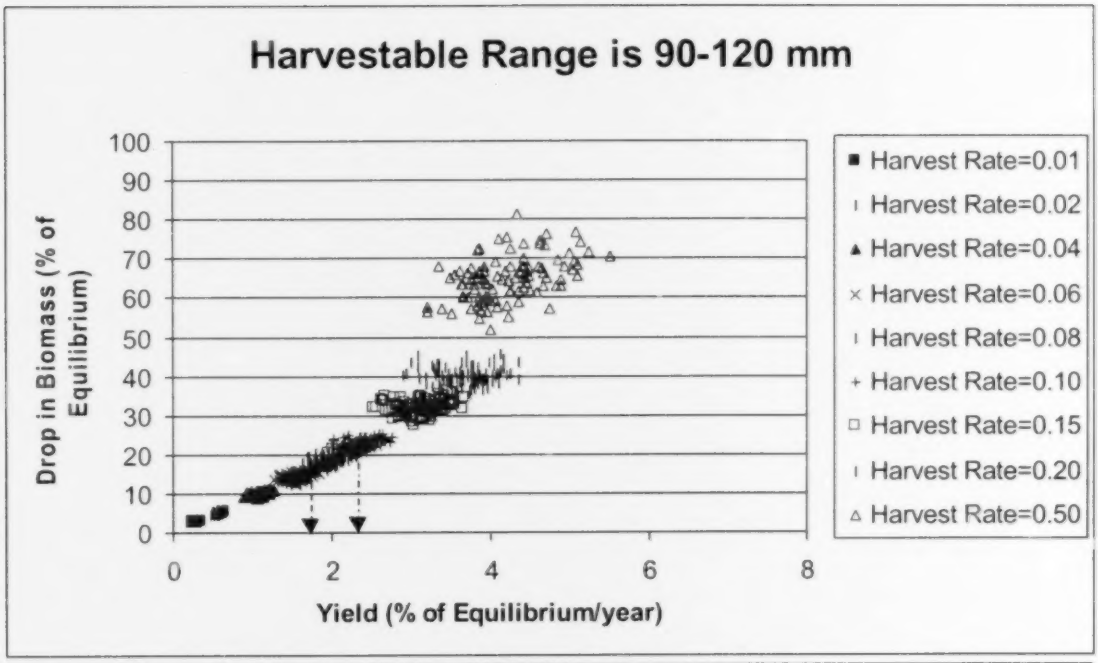

Figure A10. Yields Corresponding to a 20% Drop in Biomass

Appendix B

Preliminary Report on Egg and Yield per Recruit Analyses for a Red Sea Urchin Population

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Nanaimo, B. C., V9R 5K6

Introduction

Of interest to management are the biological implications of possible changes in various size regulations under different fishing rates to protect the valuable red sea urchin resource. Dynamic pool models, widely used in fish population dynamics studies (Quinn and Desiro 1999), require data on size at maturity, rates of growth, fecundity, natural and fishing mortality, and recruitment, some of which are difficult to obtain for red sea urchin populations. Yield per recruit and egg per recruit (YPR/EPR) analyses circumvent the requirement for detailed recruitment information by assuming recruitment is constant. Consequently, this approach was used in this paper to determine the effect of different size regulation and fishing mortality rates on a red sea urchin population. The biological input data was obtained from a productive red sea urchin population that has been studied at Kendrick Island, near Nanaimo, on the east coast of Vancouver Island, during 1990-99 (Campbell *et al.* unpublished data). There are few YPR/EPR analyses on red sea urchins. Botsford *et al.* (1993) used YPR analyses to consider periodic harvest schedules (rotation) in red sea urchins. Breen (1984), although not presenting any results of YPR analyses, discussed some implications of size limits and mortality rates on red sea urchins in B.C.

The objective of this paper is to report on the effects of two different types of size regulations on YPR/EPR under different fishing mortalities for a red sea urchin population with reasonably fast growth rates by (1) changing recruit sizes, and (2) establishing maximum sizes. The current recruit size in the fishery is ≥100 mm TD. A maximum size regulation would protect large mature red sea urchins above a certain size to allow increased potential egg production and provide additional spine canopy for small juvenile survival (Tegner and Dayton 1977; Pfister and Bradbury 1996; Lai and Bradbury 1998).

Methods

An egg per recruit (EPR) model by Tegner et al. (1989) (equation numbers up to 15, without letters) was modified by Campbell (1997, Appendix 1) to include a maximum legal size option and a size at maturity relationship. The original equation numbers (up to 15) with "a" and "p" indicate modifications to accommodate the maximum legal size option and size at maturity, respectively. In the present study, we extended these models to include a size selectivity curve and a yield per recruit model (YPR) with minimum and maximum legal size options. The EPR/YPR model was written in Java programming language by A. Meynert.

The mathematical formulae used in the models were as follows.

Egg per Recruit Model

Variable Definitions

h_j = midpoint of an interval of length measurements
w = width of each length interval
j = number of each length interval
t = time in years
M = instantaneous rate of natural mortality
N_0 = original number of female animals
t_0 = age of zero length for a von Bertalanffy length-at-age curve
K = Brody growth coefficient for a von Bertalanffy length-at-age curve
$L_{infinity}$ = asymptotic length for a von Bertalanffy length-at-age curve
L_t = the average length of an animal at time t according to the von Bertalanffy curve
SD_t = the standard deviation of length of an animal at time t
F = instantaneous rate of fishing mortality

Equations

$$\left(h_j - w/2, h_j + w/2\right); \qquad j = 1, J$$

Definition of the length intervals.

$$NV_{t,.} = N_0 \exp(-Mt) \tag{1}$$

The number of animals surviving each year in a virgin population.

$$NV_{t,.} = \sum_{j=1}^{J} NV_{t,j}$$

Number of females in a virgin population at time t for all length intervals j.

$$NV_{.,j} = \sum_{t=1}^{\lambda} NV_{t,j}$$

Number of females in a virgin population falling in length interval j for all times t.

$$L_t = L_\infty \left\{1 - \exp\left[-K\left(t - t_0\right)\right]\right\} \tag{2}$$

Von Bertalanffy size-at-age curve.

$$\mathrm{SD}_t = a + b\sqrt{t} \tag{3}$$

Standard deviation varies with the square root of age.

$$Q_{t,j} = \frac{1}{\mathrm{SD}_t \sqrt{2\pi}} \int_{h_j}^{h_{j+1}} \exp\left[-\frac{\left(h - L_t\right)^2}{2\,\mathrm{SD}_t^{\,2}}\right] dh \tag{4}$$

The proportion of animals falling into length interval j at time t.

$$NV_{.,j} = \sum_{t=1}^{\lambda} Q_{t,j} NV_{t,.} \tag{5}$$

Number of females in a virgin population falling in length interval j for all times t, calculated a different way.

$$f_j = ch_j^d \tag{6}$$

The average fecundity of an animal in length interval j.

$$E_{\max} = \sum_{j=m}^{J} NV_{.,j} f_j \tag{7}$$

The maximum number of eggs an unfished population can produce, without using the factor of a mature proportion of animals.

$$E_{\max} = \sum_{j=m}^{J} NV_{.,j} f_j MP_j \tag{7p}$$

The maximum number of eggs an unfished population can produce, using the factor of a mature proportion of animals.

$$N_{1,.} = N_0 \exp(-M) \tag{8}$$

The number of animals after one year of mortality.

$$QPR_t = \frac{1}{\mathrm{SD}_t \sqrt{2\pi}} \int_0^{h_R} \exp - \left[\frac{(h - L_t)^2}{2\mathrm{SD}_t^2} \right] dh \tag{9}$$

The proportion of animals smaller than minimum legal size at time t.

$$QML_t = \frac{1}{\mathrm{SD}_t \sqrt{2\pi}} \int_{MLS}^{\infty} \exp - \left[\frac{(h - L_t)^2}{2\mathrm{SD}_t^2} \right] dh \tag{9a}$$

The proportion of animals greater than the maximum legal size at time t.

$$NPR_{t,.} = QPR_t NV_{t,.} \tag{10}$$

The number of animals smaller than the minimum legal size at time t.

$$NML_{t,.} = QML_t NV_{t,.} \tag{10a}$$

The number of animals greater than the maximum legal size at time t.

$$NR_{t,.} = N_{t,.} - NPR_{t,.} \tag{11}$$

The number of animals of recruit age at time t, without using the maximum legal size option.

$$NR_{t,.} = N_{t,.} - NPR_{t,.} - NML_{t,.} \tag{11a}$$

The number of animals of recruit age at time t, using the maximum legal size option.

$$S_t = \left[\left(\frac{NPR_{t,.}}{N_{t,.}} \right) \exp[-M] \right] + \left[\left(\frac{NR_{t,.}}{N_{t,.}} \right) \exp[-(F+M)] \right] \tag{12}$$

The survival rate of animals at time t, without using the maximum legal size option.

$$S_t = \left[\left(\frac{NPR_{t,.}}{N_{t,.}}\right)e^{-M}\right] + \left[\left(\frac{NR_{t,.}}{N_{t,.}}\right)e^{-(M+F)}\right] + \left[\left(\frac{NML_{t,.}}{N_{t,.}}\right)e^{-M}\right] \qquad (12a)$$

The survival rate of animals at time t, using the maximum legal size option.

$$N_{t,.} = N_{t-1,.}S_{t-1} \qquad (13)$$

The number of animals in year t, based on the number of animals in the previous year and the survival rate from the previous year.

$$\begin{aligned} N_{t,j} &= NV_{t,j} && j < R \\ N_{t,j} &= Q_{t,j}NR_{t,.}/(1-QPR_t) && j \geq R \end{aligned} \qquad (14)$$

The number of animals found in length interval j at time t.

$$E = \sum_{t=1}^{\lambda}\sum_{j=m}^{J} N_{t,j}f_j \qquad (15)$$

The total number of eggs produced by a population without using a mature proportion of animals.

$$E = \sum_{t=1}^{\lambda}\sum_{j=m}^{J} N_{t,j}f_j MP_j \qquad (15p)$$

The total number of eggs produced by a population using a mature proportion of animals.

$$MP_j = \frac{L}{L + e^{(A-BL)}} \qquad (16)$$

The proportion of mature animals of length interval j.

Yield per Recruit Model

In addition to the Beverton-Holt yield per recruit model (equations from Ricker 1975), an alternate yield per recruit model was developed to allow a maximum legal size option to be used. Both models gave similar yield per recruit results when compared with similar minimum size limits. The alternate YPR/EPR model program makes use of the Baranov catch equation in combination with the other equations in Appendix B which describe the number of animals of recruit age. For brevity, only the extra equations and variables are listed below.

Variable Definitions

W_j = average weight of an animal falling in length interval j

Equations

$$W_t = aL_t^{\,b} \qquad (17)$$

Length-weight power relationship.

$$C_t = NR_t \frac{F}{F+M}(1 - e^{-(M+F)}) \qquad (18)$$

Baranov catch equation. C_t is the number of animals caught each year.

$$W_\cdot = \sum_{t=0}^{t_m} W_t C_t \tag{19}$$

Total weight of animals caught.

$$NNR_t = NR_t - NR_{t-1} \tag{20}$$

Number of new recruits each year.

$$NNR_\cdot = \sum_{t=0}^{t_m} NNR_t \tag{21}$$

Total number of recruits during the population's lifetime.

$$YPR = \frac{W_\cdot}{NNR_\cdot} \tag{22}$$

Yield per recruit.

Size-Selectivity Curve

A size-selectivity curve for the minimum legal size is approximated using five values in the YPR/EPR model program.

These equations are used for the approximation of a size-selectivity (S-shaped) curve for first entry into the fishery as an option to a knife-edge entry. Red sea urchins tests are not completely symmetrical and there can be some error (up to about 5 mm) in measuring the test diameter of urchins at the minimum legal size. A graph of a knife-edge entry would show two lines: the first running at a level of zero exposure to exploitation until the minimum legal size, at which point the level of exploitation would jump immediately to one hundred percent.

The equations used in the program split up the interval of the integral in equation (9), the equation that defines the proportion of pre-recruits at time t, into six equal parts.

Define pf(h) to be the proportion of animals at size x which are fished. Let h equal the minimum legal size. Therefore, pf(h) = 1. The user inputs values for pf(h-1), pf(h-2), …, pf(h-5). Equation (9) then becomes the sum of six equations as follows.

$$I_1 = \left(\frac{1}{SD_t^2 \sqrt{2\pi}} \int_0^{h_R - 5} e^{\frac{-(h-L_t)^2}{2SD_t^2}} dh \right) \tag{9li}$$

$$I_2 = \left(\frac{1}{SD_t^2 \sqrt{2\pi}} \int_{h_R - 5}^{h_R - 4} e^{\frac{-(h-L_t)^2}{2SD_t^2}} dh \right) (1 - pf(x-5)) \tag{9lii}$$

$$I_3 = \left(\frac{1}{SD_t^2 \sqrt{2\pi}} \int_{h_R - 4}^{h_R - 3} e^{\frac{-(h-L_t)^2}{2SD_t^2}} dh \right) (1 - pf(x-4)) \tag{9liii}$$

$$l_4 = \left(\frac{1}{SD_t^2 \sqrt{2\pi}} \int_{h_R-3}^{h_R-2} e^{\frac{-(h-L_t)^2}{2SD_t^2}} dh \right) (1 - pf(x-3)) \quad (9\text{iv})$$

$$l_5 = \left(\frac{1}{SD_t^2 \sqrt{2\pi}} \int_{h_R-2}^{h_R-1} e^{\frac{-(h-L_t)^2}{2SD_t^2}} dh \right) (1 - pf(x-2)) \quad (9\text{v})$$

$$l_6 = \left(\frac{1}{SD_t^2 \sqrt{2\pi}} \int_{h_R-1}^{h_R} e^{\frac{-(h-L_t)^2}{2SD_t^2}} dh \right) (1 - pf(x-1)) \quad (9\text{vi})$$

$$QPR_t = l_1 + l_2 + l_3 + l_4 + l_5 + l_6 \quad (9\text{l})$$

Results and Discussion

The pattern of yield per recruit at different fishing mortalities was similar for the different size limits except for ≥70 mm TD which peaked and dropped at smaller F values (Fig. B1). The F_{max} values for YPR increased with increasing minimum sizes (Table B2). F_{max} values increased with the lowering of maximum sizes because with a smaller maximum size a greater F would be required to catch available urchins within a smaller size range (Table B2).

The relative contribution of egg production (percentage of the total egg production by an unfished population at M=0.10) by female red sea urchins at various size limits and fishing mortalities is shown in Fig. B1. As F increases, fewer mature females reproduced and EPR was reduced. EPR is highest for ≥100 mm TD and lowest for ≥70 mm TD for only the minimum size limits at all F values (Fig. B1). Lowering the maximum size had a dramatic effect on protecting mature females and increasing egg production (Fig. B1).

At F=0.025 (the approximate current fishing mortality in the B.C. red sea urchin fishery) YPR was decreased from ≥80 g to <60g, but EPR increased from 73-79 % to 87-99 % when different maximum sizes were included (Table B3).

The YPR/EPR used in this paper contains, as with many dynamic pool models, oversimplifications of reality, such as constant instantaneous natural mortality for all size groups and constant recuitment. Complicating the understanding of stock recruitment of red sea urchins is the sporadic recruitment and uncertainty of the source of recruitment for a given area. Further research is required to provide more information on stock recruitment relationships and effects of density on growth, mortality and reproduction potential of red sea urchins.

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Table B1. Input parameters for yield per recruit and egg per recruit analysis using biological data collected from red sea urchins at Kendrick Island (after A. Campbell et al. unpublished data).

Parameter	Values
Minimum minimum legal size	70
Maximum minimum legal size	120
Step size for minimum legal size	5
Minimum fishing mortality	0.00
Maximum fishing mortality	0.50
Step size for fishing mortality	0.025
Maximum legal size	None, 110, 120, 130, 140
Asymptotic length L-infinity	145.634
Brody growth coefficient	0.157
Hypothetical age of zero weight t-zero	0.690
Gonad length-weight curve coefficient a	8.6424×10^{-5}
Gonad length-weight curve coefficient b	4.310
Total length-weight curve coefficient a	8.0715×10^{-4}
Total length-weight curve coefficient b	2.835
Oldest age	50
Natural mortality	.10
Original number of females	10 0
Standard deviation of length-at-age curve coefficient a	6.8319856
Standard deviation of length-at-age curve coefficient b	0
Length-fecundity curve coefficient c	16.8234
Length-fecundity curve coefficient d	3.2659
Length-maturity curve coefficient a	12.9571
Length-maturity curve coefficient b	0.1594
Length interval width	10
Proportion of animals exposed to fishing at minimum legal size – 1 unit	0.8887
Proportion of animals exposed to fishing at minimum legal size – 2 units	0.5151
Proportion of animals exposed to fishing at minimum legal size – 3 units	0.1237
Proportion of animals exposed to fishing at minimum legal size – 4 units	0.0184
Proportion of animals exposed to fishing at minimum legal size – 5 units	0.0025

Table B2. Biological reference points F_{max}, $F_{0.1}$, and $F_{0.35}$ from the yield per recruit analyses when M = 0.10 for red sea urchins from Kendrick Island at different size limits. Methods for calculating these values are explained in Quinn and Desiro (1999).

Size limit (mm TD)				
Min	Max	F_{max}	$F_{0.1}$	$F_{0.35}$
70	none	0.17	0.08	0.04
90	none	0.30	0.11	0.05
100	none	0.47	0.13	0.05
100	110	1.00	0.56	0.18
100	120	1.00	0.45	0.15
100	130	1.00	0.31	0.10
100	140	0.95	0.19	0.06
90	110	1.00	0.84	0.24
90	120	1.00	0.33	0.12
90	130	0.86	0.25	0.09
90	140	0.59	0.16	0.06

Table B3. Yield per recruit and egg per recruit (% of unfished population, 5.61E+12 eggs) results when M = 0.10 and F = 0.025 for red sea urchins from Kendrick Island at different size limits.

Size limit (mm TD)		EPR	YPR
Min	Max	(%)	(g)
70	none	73.63	87.4
90	none	77.12	84.8
100	none	79.31	81.5
100	110	99.78	9.09
100	120	98.89	20.0
100	130	96.29	34.6
100	140	88.90	54.5
90	110	99.44	14.2
90	120	98.21	24.8
90	130	95.15	38.9
90	140	87.13	58.1

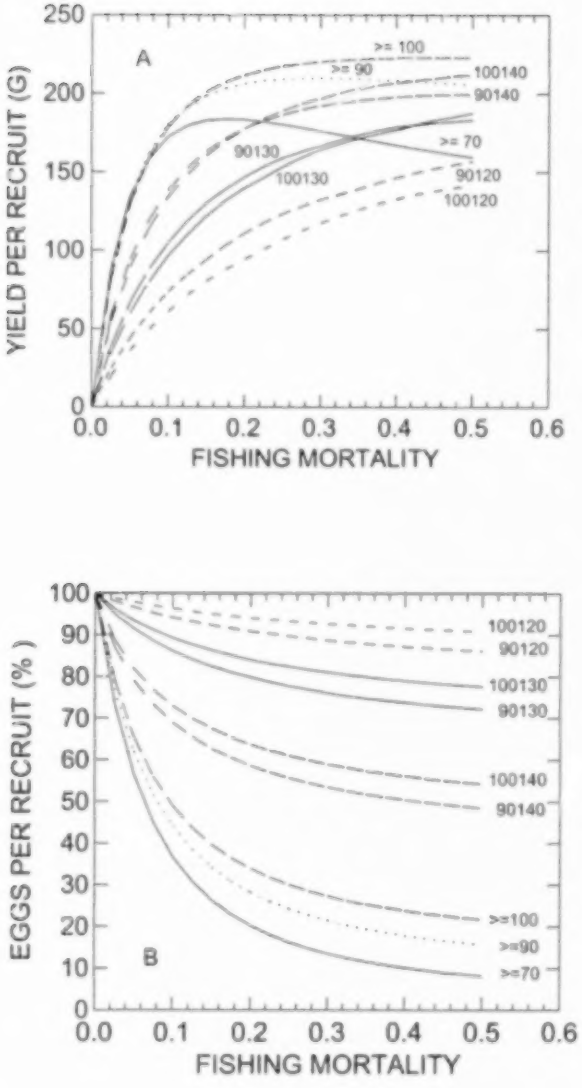

Fig. B1. (A) Yield per recruit (g) and (B) egg per recruit (percentage of total eggs of unfished population) analyses using M=0.10 and red sea urchin data from Kendrick Island. Numbers next to line in graphs indicate the different legal size limit options (e.g., 100140 indicates 100-140 mm TD).